AGARD REPORT No.721

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Fatigue Rated Fastener Systems

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AGARD-R-721

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.721

FATIGUE RATED FASTENER SYSTEMS

Edited by

H.H.van der Linden

This Report was sponsored by the Structures and Materials Panel of AGARD.

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Published November 1985

ISBN 92-835-1512-9

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

PREFACE

In recent years, the SMP has placed considerable emphasis on cooperative R & D programmes, especially where there are several variables to consider and where several identical tests must be made to evaluate the scatter in the results. Fatigue and corrosion tests lend themselves particularly well to this treatment, since one laboratory working on its own could spend a vast amount of time and money in deriving all the requisite data before any analysis of the results could be undertaken. By inviting the participation of several laboratories (even though these may be in separate countries), the work can proceed in parallel, thus reducing the total elapsed time. Moreover, each participant can reap the benefits of the whole programme for a small outlay.

Successful ventures in recent years include the Critically-Loaded Holes Programme and the Corrosion Fatigue Cooperative Testing Programme. This report presents the findings of the latest cooperative programme to be completed — an evaluation of Fatigue-Rated Fastener Systems.

Despite the advent of adhesives, composite materials, integrally-machined components and diffusion bonding, mechanical fasteners are still the most common means of joining parts together in the aerospace industry, and will remain so for many years to come. The designer needs to know which fastener systems are the most efficient, and this programme studied a number of systems from the fatigue point of view. In this context, 'system' means not only the fastener itself, but also the way in which the hole is prepared and the fit of the fastener in the hole.

The thanks of the Panel are due to the collaborating laboratories and especially to the Coordinator, Mr H.H.van der Linden, who was responsible not only for organising the programme but also for much of the analysis and the preparation of this report.

W.G.HEATH
Chairman, Working Group on
Fatigue-Rated Fastener Systems

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FATIGUE RATED FASTENER SYSTEMS
-AN AGARD COORDINATED TESTING PROGRAMME-

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SUMMARY

This final technical report contains the description, test results, analysis and conclusions of a collaborative fatigue test programme which assessed the fatigue lives of a range of fastener systems using different joint test specimen.
A range of high load transfer single shear joint designs were evaluated and compared in an extensive core programme; secondary bending and load transfer were determined experimentally.
Between seven and eight hundred specimens were fatigue tested by participants in seven countries. The fatigue tests were carried out mainly under FALSTAFF; some test series were done under MINI-TWIST and constant amplitude loading. The sheet materials used were from the 2000- and 7000- aluminium alloy series. The fasteners ranged from standard bolts to tapered fasteners, installed in holes which were drilled, broached, reamed or cold worked.
The multiple linear regression analysis method and graphical methods were used to correlate results and to find trends among the variables. In additional the cost figures were related with the fatigue performance.

The AGARD coordinated Fatigue Rated Fastener Systems programme not only identified the prime parameters in fastener system selection but also quantitatively evaluated these.
Highlights of the data indicate that:
- secondary bending prooved to be a prime parameter. At moderate to high values it tends to nullify the beneficial effect of fatigue enhancement fastener systems;
- at low to moderate secondary bending (or at the absence of it) the fit, clamping and cold work are prime parameters. At high load transfer and at high fatigue load levels the best results are obtained with cold worked holes plus high interference fit fasteners;
- double shear joints clearly show a fastener system rating;
- the hole quality as such is not a prime parameter. However, dimensioning to size to obtain a close tolerance fit results in holes with good fatigue quality;
- increasing costs of the fastener system might result in a better fatigue performance. Moderate to high secondary bending tends to nullify the extra costs of fatigue enhancement fastener systems. The conclusions of the report present a cost effectiveness rating of different fastener systems applied in double shear and low load transfer joint.

1. INTRODUCTION

The application of shear loaded fastener systems with known or advertised good fatigue performance is increasing considerably, both in new aircraft designs and in modifications of older ones. This increase in use is accompanied by an increase in research and development. The Structures and Materials Panel of the Advisory Group for Aerospace Research and Development (AGARD) recognised this and appointed working groups to carry out collaborative fatigue test programmes on fatigue rated fastener systems in aluminium alloy structural joints.

A first programme, the Critically Loaded Hole Technology Pilot Collaborative Test Programme (reference 1), was carried out in the period October 1976 up to October 1979 in which open hole and low load transfer joint specimens were fatigue tested under FALSTAFF flight-by-flight loading.
The results can be summarised as follows:
- consistent fatigue data can be generated in complex fatigue testing between the participants;
- interference fit fastener systems are relatively insensitive to effects of hole quality;
- valuable design data was generated on low load transfer joints.

After completion of the Critically Loaded Hole Technology Pilot Collaborative Test Programme a follow-on programme was defined in 1979: the Fatigue Rated Fastener Systems (FRFS) programme, coordinated by the author of the present paper.
The FRFS programme assessed the fatigue lives of a range of fastener systems using different joint test specimens. In addition the cost figures were related with the fatigue performance. A reference datum for the comparison of test results produced in different countries was established by means of "core" programmes. Results were analysed by the Air Force Flight Dynamics Laboratory (USA) and the National Aerospace Laboratory, NLR (The Netherlands). This AGARD Report describes the FRFS programme and presents the results and analysis.

2. OBJECTIVES, METHODS AND MEANS

The objectives of the cooperative programme were:
- to determine the fatigue lives for a range of fatigue rated fastener systems in different materials in combination with a selection of hole preparation techniques and installation parameters;
- to establish the cost figures of each fastener system in relation to its fatigue performance;
- to identify the prime parameters involved in fastener system selection;
- to generate design data for a number of fastener systems;
- to develop a reference datum for the comparison of test results produced in different countries using different specimen geometries;
- to develop experimental methods for fastener system fatigue rating.

Seven countries participated in the programme (table 1). As a first step each participant defined his own programme, which could be active, planned or desired. This definition specified plate material, thickness, surface treatment, interfay surface sealant, final hole production tooling, fastener type, fastener fit, fatigue loading programmes and load levels. The participant's programmes formed a total matrix of testing variables. Elements of the matrix, for instance load level and specimen geometry, were adjusted to give good overall problem coverage without unnecessary duplication. Further, a number of additional programmes, the "core" programmes, were defined to allow comparison of results produced in different countries using not completely identical specimen designs.

For clarity the FRFS programme was split up in four parts:

- No load transfer joints (NLT).
- Low load transfer joints (LLT).
- Double shear joints (DS).
- Single shear joints (SS).

with each part having its own basic and core programmes.

For all specimens of the FRFS programme fastener fit and sometimes hole surface roughness were measured during fastener installation.

The specimens of the FRFS programme were tested mainly under FALSTAFF (Fighter Aircraft Loading STandard For Fatigue evaluation) loading; some test series were carried out under the gust spectrum MINI-TWIST and under constant amplitude loading. No crack growth observations were made. Each fatigue test was reported on an special form.

Fatigue lives were evaluated in terms of:

- fastener system, fit and hole quality;
- installation cost figures;
- joint geometry, i.e. load transfer and secondary bending;
- plate material;
- load spectrum.

A statistical analysis method and graphical methods were used to correlate results and to find trends among the variables.

Since there was a lack of a single shear standard specimen, a range of high load transfer single shear joint designs were evaluated and compared in an extensive core programme. The latter included fatigue testing of the single shear specimen together with a double shear equivalent design. All specimens were manufactured from one material.
Three different fastener systems (hole quality, fastener and fit) were selected and defined; the third fastener system was optional. Surface treatment, interfay sealant, load levels and load spectrum were specified.

3. PROGRAMME OVERVIEW

As originally envisaged the FRFS programme consisted of separate programmes of testing directed to the requirements of individual laboratories and linked by additional core programmes; Annex I gives the original schedule. The FRFS programme overview, together with characteristic specimen examples, is presented in table 2. The four programme parts are described in the next subchapters.

3.1 No-load transfer joints

The no-load transfer specimen has a continuous dogbone member. The single fastener mounts a small non load carrying plate to the dogbone (figure 1a,b). Load transfer is close to zero and secondary bending is negligible. If testing of this joint type results in the same fastener system rating as for other types of joints, e.g. the low load transfer joint, then this simple and cheap design can be used for the evaluation of fastener systems.

The two basic programmes defined differed in intention and goal: Sweden would evaluate four fastener systems in one sheet material, while France would evaluate four sheet materials using one fastener system. Therefore a limited core programme was defined to allow comparison of the results of the two basic programmes. Table 3 overviews the programme originally defined. In addition to no-load transfer specimens Sweden also tested open hole ones (figure 1c).

3.2 Low load transfer joints

This part of the programme (table 4) may be considered as a supplemental one to the Critically Loaded Hole Technology Programme in that individual participants could investigate further the fatigue resistant fastener systems of particular relevance to them. The standard low load transfer reverse double dogbone is shown in figure 2. For 6.35 mm nominal diameter interference fit fasteners the load transfer at each fastener location is approximately 5 % of the axial load. The joint is representative of lower wing skin panels attached to spars, for example. A core programme was defined to allow comparison of results obtained using the deviating UK design (figure 2c) with the results obtained by the other participants. Note that the UK design was already being tested when the FRFS programme began.

3.3 High load transfer double shear joints

Double shear joints have no secondary bending. Table 5 shows the test schedules. Since different specimen geometries (figure 3 to 8, 12), sheet materials and thicknesses, fastener systems and spectra were used it was felt necessary to define a core programme to evaluate and compare the different designs. Unfortunately, the double shear core programme was cut short during the course of the programme. The UK cancelled their contribution since no differences in fastener rating were observed comparing low load transfer and double shear specimen results. The Swedish programmes and the Netherlands part of the double shear core programme could not be completed for economic reasons.

3.4 High load transfer single shear joints

Single shear joints are exposed to secondary bending caused by asymmetric eccentricities of the load carrying members. The amount of bending depends strongly on the joint geometry. It is generally recognised that differences in fastener systems tend to be overshadowed by excessive bending. Representation of a realistic bending situation by individual participants resulted in a number of different specimen geometries. These were evaluated under a range of variables directed to the requirements of individual participants (table 6).

3.4.1 Background of the single shear designs

Four designs will be described (figures 7 to 11):

- lap joint, a three row-type (F) and a two row-type (US);
- X-type joint (SW);
- Q joint (UK);
- 1½ dogbone specimen.

Lap joints are used in an aircraft structure only if a double strap can not be applied. This type has a very high bending stress, which is in the order of the axial stress component. At least two fastener rows are present. In a two row lap joint the load transfer per row is 50 % of the total load. The load transfer decreases somewhat when three rows will be present. Due to the high bending and high load transfer this joint is the most fatigue critical one, i.e. it will give the shortest fatigue lives.
One might argue that this specimen is unrealisticly severe because in the aircraft structure the bending is reduced by the support of other structural elements, e.g. stringers or ribs. Nevertheless, the fatigue data generated using the lap joints are used as one of the extreme data sets in between which a designer interpolates to obtain fatigue life estimates for his joint configuration. The US lap joint specimen (figure 8) is a standard one of MIL-STD-1312 (Method 2?, 15 December 1977).

The 1½ dogbone specimen might be considered as a standard one within the AGARD community: it is used in the corrosion fatigue testing programmes CFCTP (Corrosion Fatigue Cooperative Testing Programme) and FACT (Fatigue in Aircraft Corrosion Testing). The specimen simulates the load transfer and secondary bending characteristics of runouts of stiffeners attached to the outer skin, and was developed by the Laboratorium für Betriebsfestigkeit (LBF) in West Germany. The design goals were a load transfer of 40 % and a secondary bending ratio of 0.50 (figure 11).
However, an investigation (reference 2) suggested that in this type of specimen the load transferred was unrepresentatively low and dependent upon the type of fastener installed. Further, reference 3 shows a relatively low load transfer and indicates a fastener fit dependence.
The compression limit load is about - 10 kN, i.e. a specimen without anti-buckling guides will not buckle when compression loads do not exceed - 10 kN. The (bolted) grips and clamping-in procedure are well documented (reference 4).

In the UK an alternative specimen was designed (reference 5) that attempts to alleviate some of the problems associated with e.g. the 1½ dogbone joint.
The alternative design, the Q joint (figure 10), is based on a single lap joint, but the addition of a further load carrying member controls bending by providing extra lateral stiffness. Further, the double shear connection at the second fastener row ensures that fatigue failures do occur at the single shear connection.
The advantage over the 1½ dogbone lies in the fact that it is a 100 % load transfer joint. In the 1½ dogbone the load can by-pass the fastener in a clearance condition before load is transferred in bearing.
In the Q joint the stiffer double shear connection might be expected to transfer more load than the single shear row; thus, a load transfer somewhat lower than 50 % is expected.
Initial testing (reference 5) suggested that the bending ratio is approximately 0.5; this ratio may decrease to a value nearer to 0.4 under dynamic loading conditions. A disadvantage is that the Q joint is more complicated and thus more expensive than the 1½ dogbone.

The X type (figure 9) is a Swedish development. It is a two row joint because a known load transfer, independent of the type of fastener, may be obtained with a maximum of two rows. The design has splice plate areas equal to the base plate areas, implying a theoretical 50 % load transfer per row and independent of fastener stiffness. The splice plate centres of gravity coincide with the base plate centre of gravity, implying zero gross eccentricity and no major secondary bending. Compared to other splice plate configurations (reference 6) the X type had the most uniform load transfer distribution over the fasteners. Further, the splice plate stiffening effect is very local.

3.4.2 Core programme

Primary objective of the core programme was to evaluate and compare different designs in use in the participating institutes and companies. To obtain an impression of the influence of bending on the fatigue life, so called "double shear equivalent specimens" were derived from the single shear ones (figures 8, 11, 12) in which the asymmetric side sheet of the single shear design was replaced by two symmetrically placed side sheets each having half the thickness of the original one. The double shear feature excludes secondary bending.
However, load transfer might not have been completely identical in the two designs because of changed fastener tilt and bending characteristics and the presence of two locations of frictional load transfer instead of one.
Table 7, which reviews the core programme, shows as an example, the 1½ dogbone specimen and its double shear equivalent design.

All specimens in the core programme, namely all single and double shear designs, were manufactured from one material, i.e. the 5 mm thick 7050-T76 core programme material, which was furnished by the US. Surface treatment, laterfay sealant, load levels and load spectrum were specified (Annex 1). Two fastener systems were selected and specified (Annex 2):

- Fastener system A: a countersunk Hi-Lok installed with clearance fit in a reamed hole (FKFS-A).
- Fastener system B: a countersunk Hi-Lok installed with interference fit in a cold worked and reamed

hole (FRFS-B).
A third, optional, fastener system was defined because of completeness; this fastener system also had a countersink Hi-lok but it was installed with high interference in a reamed hole.

All core programme specimens then were fatigue tested to failure under FALSTAFF flight simulation loading. As in the other programmes, fit and surface roughness were measured during fastener installation (Annex 3). In addition to the fatigue tests, one specimen of each combination of specimen design and fastener system was instrumented with strain gauges to measure load transfer and secondary bending.

3.5 Access to all details

The programme overview showed that various joint geometries were used to evaluate different materials, bolts, fastener systems, etc.

The tables refer to:
- figures 1-12 for specimen configuration details;
- table 8 for the mechanical properties of materials;
- table 9 for the faying surface treatment details;
- table 10 for the fastener systems.

It should be noted that the presentation of application and manufacturing instructions is beyond the scope of this report.

4. TEST PROCEDURES

The stress levels are given as gross area stress, unless otherwise indicated. Guidelines for testing have not been given since the Critically Loaded Hole Technology programme (reference 1) showed that:
- the participating laboratories could apply spectrum loads satisfactorily;
- there was the ability to generate consistent data in complex fatigue testing between the participants;
- all the data generated at different laboratories were accepted by all participants.

4.1 Measurement of load transfer and secondary bending

Based upon the procedures of the LBF (FRG) and upon experience of SAAB-SCANIA and FFA (SW), RAE (UK) and the NLR (NL) standard procedures were developed (references 7, 8); these procedures are also given in Annex 4.

Each single shear joint was instrumented with a large number of strain gauges to determine the load transfer and secondary bending. Load transfer was also measured on the double shear equivalent specimens of the single shear core programme.

4.1.1 Secondary bending

Secondary bending is of interest at the fatigue critical cross section. Usually a crack started at a hole or at the faying surface close to a hole. The location of crack initiation was not accessible in most cases, so a neighbouring position was chosen for the measurement. The conventions adopted by the working group are given in figure 13. Jarfall (reference 9) showed that displacement of the strain gauge by 1/8 of a fastener diameter in the transverse direction changed the secondary bending by not more than 1 to 2 %; so the accuracy of positioning in transfer direction was not too critical. Positioning in the axial direction required a higher accuracy since the strain gradient was very steep: for a point at the same distance on the opposite side of the fastener the secondary bending was of the same order of magnitude but of reversed sign. Jarfall (reference 9) confirmed this using measurements on X type joints.

4.1.2 Load transfer

By definition the load transfer is the percentage of the total load transferred at a particular point of load transfer. The by-pass load (figure 13) was thus measured aft of each fastener row.
Measurements by Eriksson and Magnusson (reference 10) showed that the strain distribution aft of the fastener row is not uniform; therefore, a row of strain gauges was bonded to allow integration over the member width. In order to minimize the number of strain gauges, strain gauges were bonded only at maxima and minima of the strain distribution.
Further, the gauges were located at equal distances (in the load direction) from points of load transfer. The distance between two fastener rows was usually 4 fastener diameters; thus the gauges were bonded at 2 diameter aft of the fastener row. Also strain gauges were bonded at both sides of the sheet to determine the axial strain (figure 13), which was used for the determination of the by-pass load.

4.2 Data recording

Individual data sheets were completed for each specimen:
- the measurements of fit and surface roughness were recorded on the data sheet (Annex 3);
- an example of the test data sheet, originating from the UK, is given in table 11;
- the data sheet for reporting the load transfer and secondary bending measurements, see Annex 4.

5. SPECTRA

The fatigue tests were carried out mainly under FALSTAFF (Fighter Aircraft Loading STandard For Fatigue). A minority of the test were done under the gust spectrum MINI-TWIST.

5.1 The manoeuvre spectrum FALSTAFF

FALSTAFF has been based on a large number of actual flight load-time histories pertaining to five different fighter aircraft types operated by three different Air Forces.
The essential properties may be summarized as follows:

- FALSTAFF represents a load sequence, defined by successive peaks and throughs, covering a "block" of 200 flights.
  This block size conforms with average european annual fighter utilisation.

- The flights in FALSTAFF belong to three different groups of mission types: flight with repetitive patterns of severe manoeuvring (e.g. air-to-ground missions), flights with severe manoeuvring (e.g. air combat) and flights with only light to moderate manoeuvring (e.g. navigation mission).

- The FALSTAFF sequence contains taxi load cycles. The majority of these taxi load cycles are associated with a crossing of zero-stress level.

- The complete FALSTAFF sequence consists of 35966 numbers, ranging from 1 to 32.
  This complete sequence is contained in tabular form in reference 11. Moreover, this reference includes a complete FORTRAN listing of the program to generate FALSTAFF.

- The "FALSTAFF load levels" ranging from 1 to 32 are Arbitrary Units. However, "zero"-stress level corresponds with FALSTAFF-level 7.5269.
  The smallest load variation ("omission level") considered is two FALSTAFF levels or approximately 8 per cent of the highest stress contained in FALSTAFF. The highest stress ("truncation level") considered is the one exceeded once per hundred flights.

Figure 14 and figure 15 show the load spectrum of FALSTAFF and some FALSTAFF flights respectively. The severity of the spectrum is usually identified by referencing the stress that a test specimen experiences at the highest load level in the spectrum. In this report the same convention is used.

5.2 The standard load sequences for transport aircraft wings TWIST and MINI-TWIST

The development of the standard TWIST (Transport Wing STandard) is fully described in reference 12. For testing purposes the spectrum has been approximated by the stepped function shown in figure 16. Stresses are expressed non-dimensionally by dividing them by the stress pertaining to undisturbed cruising flight, S_{mf}. There are ten gust load levels and one taxi load level. TWIST consists of blocks of 4000 different flights.

There are ten different flight types, ranging from storm (A) to calm (J) conditions. The frequency of occurrence of each flight type and of each load level within each type of flight is reported in table 12. The load sequence is completed by defining the sequence of application of the different flights and the sequence of loads within each flight. Basic properties of the defined sequences are:

- The flights and loads for each flight are applied in a random sequence except that clustering of severe flights is not allowed.

- The loads within each flight are applied as a random sequence of half-cycles such that a positive half-cycle is followed by a negative half-cycle of arbitrary magnitude.

- Load sequences are generated individually for each flight. Thus flights of the same type generally have a different load sequence.

The positions of the severest flights in TWIST are: 1656 (type A); 2856 (type B); 301, 2936 and 3841 (type C).
The highest load to be included in the spectrum was chosen as the load that is exceeded approximately 10 times per aircraft life, or once per 4000 flights.

The main difference between TWIST and MINI-TWIST is that the latter contains considerably less load cycles of the smallest amplitude, resulting in approximately 15 load cycles per flight (table 12).

In the Fatigue Rated Fastener Systems programme a part of the tests were carried out under MINI-TWIST, which was truncated at level III; this version is designated as MINI-TWIST III.

The characteristic stress level is the mean stress level in flight, S_{mf}.

5.3 Constant amplitude loading

Some test series were also carried out under constant amplitude loading, having a stress ratio R (= minimum stress/maximum stress) of 0.1. The stress level indicated is the maximum stress.

6. METHODS FOR ANALYSING THE FRFS PROGRAMME DATA

A statistical analysis of the FRFS programme data has been carried out by Mr. I.M. Potter, Air Force Wright Aeronautical Laboratories, Dayton, Ohio, USA. It was assumed that each participant of the FRFS programme would use adequate statistical methodology within the portion of the programme for which they held responsibility.
The Northwest Analytical STATPAK software was used to perform the statistical analyses. The analysis methodology used was that of multiple linear regression. This methodology was chosen since it is useful where there exists more than one component effecting the performance of a product. In the FRFS programme the fatigue life is a product of several parameters (e.g. specimen design, stress, fastener type, material, interference, interfay treatment, hole quality) whose interactions are not specifically defined. The FRFS programme compounds the problem by adding the variables of differing test organisations and manufacturing processes to result in a final report which has numerous intrinsic variations.

Multiple linear regression approaches assume that two or more variables are related to each other with an equation of the form given in equation 6.1.

$$Y = B0 + B1 * X1 + B2 * X2 + B3 * X3 + \ldots + BN * XN \qquad (6.1)$$

where Y is the dependant variable and the X's are the independent variables and the B's are the coefficients which are calculated in the regression process. The STATPAK programs assume that there is no significant interaction between the independant variables and that each variable contributes approximately equally to the regression.
As a complation of the statistical analysis the following correlations were made graphically:

- open hole joints vs no load transfer joints;
- no load transfer joints vs low load transfer joints;
- low load transfer joints vs double shear joints;
- secondary bending vs fatigue life;
- load transfer vs fatigue life;
- fatigue performance vs cost.

7. RESULTS OF THE FATIGUE RATED FASTENER SYSTEMS TESTING PROGRAMME

7.1 Presentation of fatigue life data

The complete set of fatigue life data for the FRFS programme is given in the tables 6-1 to 6-21 of Annex 6; the framed numbers are the log mean life figures.
The fatigue life data are plotted in figures 17 to 41 inclusive per participant and test schedule.
All stresses are gross area stresses, unless otherwise indicated.

7.2 Results of the measurements of secondary bending and load transfer

Secondary bending and load transfer have been determined on reverse double dogbone specimen, the single shear and double shear core programme specimens using standard instrumentation and procedures. Full details of the measurements are given in Annex 5, which also presents the secondary bending and load transfer as function of applied load. Table 13 summarizes the values of secondary bending and load transfer at the fatigue test stress levels.

The following deviations from the standard procedures and instrumentation were observed:

- the French type D double shear joint had broached instead of reamed holes; since the fit was within the specified range, this should not influence the results;
- the US type C2 lap joint was not instrumented according to the FRFS requirements: the secondary bending gauges were located too far from the fasteners. Therefore, a bending value was recorded which was too low. Further, contrary to its condition during the fatigue testing the specimen had no bending restraint during the measurements. No load transfer gauges were applied; the load transfer is estimated to be close to 50 % because the specimen is a two row joint;
- the double shear equivalent design of type C2 (USA) had side sheets which had twice the thickness as was specified. Moreover, the load transfer gauges were bonded only at the locations giving the lowest response, i.e. directly behind the fastener;
- the surface treatment of the French core programme specimen had only epoxy paint as surface treatment instead of primer + sealant;
- the Swedish X joints were provided with oversized holes.

7.2.1 Reverse double dogbone specimen

As an addition to the programme France instrumented and tested reverse double dogbone specimens, one set being made of 2024 and one of 7075, each containing two Hi-loks mounted with high interference in reamed holes. Because this fastener system (and in particular the fit) were not the same as the core programme fastener systems (FRFS-A and -B) the results of the measurements cannot be compared directly with the results of the core programme measurements. Nevertheless, the results show interesting trends. There is a large difference in secondary bending and load transfer behaviour between the 2024- and 7075-alloy specimens. Secondary bending and load transfer are higher for the 2024-alloy specimen: the secondary bending ratio of .26 might be considered as a very high value for this joint type.
It is noted here that the clamping procedure is crucial when using wedge type grips; exploratory tests at NLR showed that load transfer might even reverse if no special precautions were taken. It is essential to prevent relative motion of the two dogbones at the typical ends when clamping in. The solution used at NLR is given in figure 42. Germany used a pin loaded hole solution, figure 2b.

7.2.2 Core programme single shear joints

The effect of applied load on secondary bending is large for lap joint type specimen. A more moderate effect is observed on the Q type. The same classification applies to the effect of the fastener system on the secondary bending. A remarkably low bending is observed at the FRFS-A (clearance fit) 1½ dogbone specimen. The latter type shows more clearly the effect of the fastener system. In general the load transfer is less affected by the applied stress. Further, the influence of the fastener system on the load transfer variation is small for the lap joint and 1½ dogbone, and very small for the Q type joint.
No secondary bending and load transfer measurements are available for X type joints with FRFS-A and -B. For reasons mentioned in 3.4.1 the load transfer is 50 % and is independent of the fit. The secondary bending ratio, determined in another programme, is about 0.80.

7.2.3 Core programme double shear joints

The C1 and D types show a negligible dependence of load transfer on the applied stress level. In both types the first fastener row, i.e. the first row where load is transferred from the base to the side sheets, has the highest load transfer, while the one or two fastener rows in the middle contribute only a little to the load transfer. The locations of highest load transfer correspond with the failure initiation sites. The change from a clearance fit to an interference fit results in an increase in end row load transfer and a decrease in load transfer in the middle fastener row(s). No load transfer measurements were made on type M_1, M_2 and H_1. The last is a two row joint i.e. it has a load transfer of 50 % whilst the load transfer of M_1, M_2 is estimated to be about 20 %.

7.3 Measured fit and surface roughness

The tables that present the fatigue life data, see Annex 6, give characteristic values of applied fit, either as an average value or as a range. The programme called for the measurement of fit and hole surface roughness. Some participants limited their efforts to the measurement of the diameter of a sample of the fasteners and holes. The participants will report in detail on the measurements made. Hole surfaces roughness measurements were only made by two participants and are therefore not presented.

7.4 Cost of fastener systems

The cost of fastener systems consists of:

- equipment and tools;
- purchase cost, which depends on fastener type, fastener material and number of fasteners ordered;
- preparation of tooling, sealant etc.:
- installation:
  - positioning of tool
  - predrill
  - clamp
  - drill
  - deburr
  - inspection of hole
  - application of sealant/primer in hole
  - installation of fastener
  - inspection of fastener.

Table 14 reviews available information; cost are transposed into US dollars. The purchase cost per fastener drop sharply when the number of purchased pieces increases; for some fastener systems this is illustrated in figure 44. The relative cost of fastener systems can be compared using table 15. A comprehensive cost comparison can not be made because the total expenses should include not only the total direct costs such as fastener purchase cost and manhours for installation, but also writing off of equipment, cost of tooling, manhours for preparation, etc. The latter three cost elements can not be given as cost per fastener installation because the information necessary for this depends on the number of fasteners per component, total number of components etc. For illustration figures 45-46 detail the contribution of some cost elements that contribute to the total installation expenses. Evaluation of the costs of different fastener systems is very diffi[illegible]
First, the participants' dat[illegible] n the same fastener system deviate widely, as illustrated by the Taperlok system data. Nevertheless, this is the most time consuming fastener system. Special precautions should be taken to ensure that the structure is securely clamped together. Checking the hole for bearing area is a time consuming but essential operation. All operations must be closely controlled and carried out by skilled personnel. The cost of this tapered fastener is high, but the cost of equipment and tools does not exceed that of standard fasteners. These costs are high for the equipment for cold work processes of which the sp[illegible]t sleeve is the most time consuming. This is caused by the need to remove the sleeve and ream to size. It is noted that reaming and countersinking after the actual cold work process is not necessary any more in a new version of this cold work system.

7.5 Locations of primary fatigue crack origins

The programme description required the evaluation of fatigue lives in terms of fatigue crack initiation sites. Halfway through the programme all participants were requested to send fractured specimen halves to the NLR. It was the intention to examine and to determine the fatigue crack origins at a single source followed by the classification of the crack origins. However, this goal could not be achieved up to the moment the report was written. Fortunately, some participants identified and reported the primary fatigue crack origins themselves.

8. CORRELATION ANALYSIS

8.1 Correlation of fatigue lives of open hole specimen and no load transfer joints

Figure 17 presents the open hole specimen and NLT joint fatigue life data for the 2024 and 7010 alloys. Both specimen types do not end up with the same fatigue lives; the NLT joint gives the longer lives, except for the 7010 alloy in the lower stress level region. Further, the 7010 and 2024 alloy results, for each specimen type, are relatively close, but again with above exception.
The results show that the presence of a transition fit fastener tends to give better fatigue lives compared to the open hole situation.

8.2 Correlation of fatigue lives of no load and low load transfer joints

Fatigue test data of both designs are available only for 2024 and 7050 specimens having an interference fit Lockbolt fastener system (figure 47). The 7050 results are very promising; the slope is the same for both designs, while the low load transfer joints have a somewhat shorter fatigue life. The lives of the 2024 alloy specimen tested at the unrealisticly highest stress level are short. At the lower stress levels the slope is never the same for the two joints. But the general picture is, for both materials, that there is no significant difference in trends between the no load transfer and low load transfer joints. The statistical analysis indicates that a possibility exists that the no load transfer specimens could be substituted for the low load transfer joints to evaluate fastener systems. The likelihood of the same fastener rating being observed in both specimen designs cannot be considered on the basis of the present results. It can only be concluded that the results point towards similar trends of the effect of stress level on the fatigue life.

8.3 Low load transfer joints fatigue life analysis results

The statistical analysis was limited to those specimens where the holes were not cold worked prior to fastener installation. A cold working independent variable would be possible but the data packages received did not contain the cold hole expansion measurements.

The data were analysed with the only variables which had specific quantification associated with them; they were (1) fatigue life, (2) applied stress and (3) fastener interference. The effect of reaming compared with drilling of the fastener hole was analysed separately in the case of the 7000 series aluminium specimens. The fastener interference was given as a positive number if there was interference between the pin and the hole; if there was clearance the interference was assumed to be zero for purposes of this analyses. In those cases where a range of interferences was specified, the mean of the range was assumed. All material results were considered as a part of either a 2000 or a 7000 series aluminium pool.

The multiple linear regression analysis results are given in equations 8.1 and 8.2 for the reverse double dogbone 7000 and 2000 series aluminium alloy specimens, respectively.

$$N = 10 \wedge (5.734 - (0.006127)*\text{Stress} + (0.00364)*\text{Interference}) \qquad (8.1)$$

$$N = 10 \wedge (7.075 - (0.013322)*\text{Stress} + (0.02210)*\text{Interference}) \qquad (8.2)$$

where

N = fatigue life in flights (FALSTAFF)
Stress = maximum spectrum stress, MPa
Interference = difference between fastener and hole size, μm

The equations make sense in that the higher the stress, the shorter the fatigue life and the higher the interference the longer the life, as many investigations have confirmed qualitatively. The equations indicate that, for the range of data investigated, the 7000 series alloys have a longer fatigue life and have a steeper slope relative to the effect of stress than the 2000 series aluminium. At zero interference the crossover where the 7000 series becomes shorter lived is at a stress of 180.9 MPa and a life of 42250 flights.

A review of the data indicates an interesting trend in the effect of interference on fatigue performance. The coefficients of the 2000 series data are a factor of six greater than those of 7000 materials. It may be an unfair comparison since the majority of the 2000 coupons were manufactured within the range of 15 to 40 μm interference with only the USA specimens at zero clearance (prior to rivetting) for two types of aluminium rivets which are themselves not considered to be high-performance, fatigue rated fasteners. The effect of interference calculated here is grossly overstated for the 2000 series aluminium coupons. The 7000 series data are considered to be more typical of interference fit fastened low load transfer specimens. The 7000 series data indicate that interference between fastener and hole result in a factor of approximately 50 percent increase in fatigue life for 50 μm (0.002 inches) hole interference.

The analyses fit the data as can be seen in figures 48 and 49 for the 7000 and 2000 series aluminium alloy materials, respectively. In the 7000 series data, the multiple linear regression curve at zero interference appears to fall in the middle of the data whereas the 2000 series regression line is at the lower limit of the data. The 2000 series regression line appears to go through the middle of the USA data which had squeezed rivets installed. As discussed in the previous paragraph, the USA data were used as zero clearance data in the analysis; it is noted that some interference will be present after rivet installation.

Since the other data are significantly offset to the right of the USA data, the regression indicated a strong effect of interference on fatigue life for the 2000 series specimens. The 7000 series data has a much smaller coefficient of interference.

The data from the 7000 series aluminium alloy specimens were analysed in an attempt to determine the effect of drilling versus reaming of the fastener holes. This analysis illustrates one way to avoid the problem of calculating where a parameter has no quantitative variable associated with it. In this case, the independent value '1' was assigned to those specimens which were reamed and the value '0' to those which were drilled. In order to equitably complete this analysis the French specimen series which had broached holes were removed from the data set. The result is given in equation:

$$N = 10 \wedge (5.5974 - (0.00575)*\text{Stress} + (0.00380)*\text{Interference} - (0.000812)*\text{Ream}) \qquad (8.3)$$

This equation is somewhat different from that of Eq. 8.1 not only because an additional term has been added but also because ten (10) specimens were removed from the data set when the French specimens were deleted. Note that the coefficients of the mean, stress and interference variables were changed less than 10 percent from those given in Eq. 8.1. The coefficient to the "Ream" variable is given as -0.000812. Since the "Ream" variable is limited in value to either '0' or '1' the effect on the equation is minimal from this coefficient. A typical effect of the "Ream" variable would be to change the fatigue life less than one per cent. This analytical result should not be taken to be a recommendation to discontinue reaming, though. Reaming is of importance in making a precise hole in which a fastener may be installed at a known interference. Thus, the effect of reaming may already be included in the analysis in another independent variable such as "interference".

Systems that stand out in figure 48 are the French broached hole specimens with Lockbolt fasteners and the Netherlands double margin drilled holes compared to their standard drilled counterparts. These data were not further investigated using the multiple linear regression since there was no way to quantify the hole quality parameters.

In figure 49, the Italian test specimens at 280 MPa stand out above the remainder of the 2000 series aluminium specimens. Here, again, the French broached hole specimens have lives at the high end of the pooled fatigue life data. The USA aluminium riveted specimens reside at the lower end of the fatigue life data.

The multiple linear regression analysis methodology has been shown to be useful in determining the impact of different test and manufacturing processes on the fatigue performance of the AGARD reverse double dogbone specimens. The greatest success has occurred when the parameter of interest can be quantitatively defined so that its impact on fatigue performance can be calculated.

The multiple linear regression analysis results quantify -for instance- the effect of interference, whilst no information is given of the scatter. To illustrate the latter the ranges of fit and corresponding fatigue lives were plotted (figures 50, 51), showing that scatter is certainly not negligible when selecting fastener systems.

The beneficial effect of interference is illustrated clearly by the German results. MBB/VFW calculated the stress situation close to the fastener hole. Figure 52 shows that a fastener oversize of 15 μm (Ø 6.35 mm) results in a tangential stress of about 94 MPa. An increase in fit to 40 μm gives a tangential stress of 250 MPa. The net effect of the interference fit approach is to reduce the alternating component of the stress while increasing the maximum one. The determination of the optimum interference is difficult. The increase in fit from a medium to a high value with the Taperlok gives only a moderate improvement in life. An interference of one per cent of the fastener diameter, in this case, might be considered as an optimum value (reference 13). No significant differences in life are observed when comparing the titanium and steel fasteners. Further, the fatigue quality of the double margin drilled holes is certainly not worse than that of the reamed holes.

The Italian results suggest that, in low load transfer joints, the effect of cold working is spoiled by subsequent application of a clearance fit. Further, the effect of hole diameter is fairly small, giving longer lives for the 5 mm hole. The differences in the life are small when comparing protruding, countersink, and tension countersink Hi-loks.

Disregarding the small differences in life improvement factors the same trends are found under FALLSTAFF and MINI-TWIST III loading. However, scatter is larger under MINI-TWIST III loading (France, the Netherlands).

The hand bucked rivets, in low load transfer joints, give longer lives than the machine squeezed ones. This is more pronounced for the 2024 rivets than for the 7050 rivets.

The numerous fastener systems evaluated in the UK are discussed in detail in 8.5.

8.4 Comparison of UK and AGARD low load transfer joint design

The fatigue test results for the low load transfer standard specimen are given in Annex 6 and are shown in figure 28 along with the results of the UK main programme. Whilst the clearance fit results are very similar it should be noted that the life improvement due to cold working is greater in the AGARD joint than in the UK joint. The X-ray diffraction measurements of Dietrich and Potter (reference 14) indicate that the compression region around a cold expanded hole extends to a size approximately that of the hole diameter in large plates. Since the UK design LLT specimens have such short edge margin, it is possible that as high an amount of cold working could not be developed resulting in the lower fatigue life seen here. It is noticeable from the UK fracture surface examinations that the cold worked specimens have different failure modes: the UK joint failing from a fretting origin away from the bore of the hole whilst the AGARD joint fails from origins at the bore of the hole. It could be argued that the UK joint is strongly affected by cold working, since the failure origin is moved completely away from the hole.

8.5 Correlation of fatigue lives of double shear and low transfer joints

Results from France and the UK show that the lives of the reverse double dogbones are -comparing the means- shorter than the lives of the high load transfer double shear joints (figures 53-56), but scatter-bands may overlap (partly). The Dutch results (figure 57) show the contrary: the low load transfer joint has better fatigue characteristics than the HLT double shear joint. Next the fastener system rating in both designs is compared.

From figure 53 it follows that the UK results have a drawback when comparing the double shear and low load transfer joints: the test stress level ranges differ. Without considering this it is observed that the low load transfer joint mean results are situated in two clusters, clearance fit fasteners versus cold-worked holes or interference fit fasteners. With the exception of the Huckcrimp system, used on low load transfer joints, significant life improvements were gained by using life enhancement systems. The reason why the Huckcrimp fails to increase the fatigue life over the Hi-lok system is because the improved clamping has little effect in low load transfer situations. In high load transfer joints clamping can significantly improve the fatigue performance by providing a load path which by-passes the fastener.
The high load transfer joint results show that life improvement mechanisms are obviously more effective where the potential for improvement is the greatest. Improved clamping will have an effect only when a large load is transferred by the fastener; frictional clamping then becomes significant. With higher load transfer and/or higher alternating stress, i.e. when the relative movement between fastener and joint material is large, the interference fit reaches its full potential, resulting in a delay in the onset of cracking.
Cold working also delays the onset of cracking and due to the compressive residual stress field also retards early crack growth.
Comparing the fatigue lives of the Huck-EXL and the Hi-tigue fasteners (figure 54), the UK results suggest that both joints are not equivalent with regard to the rating of the fastener systems considered.

8.6 Double shear joints fatigue life analysis results

8.6.1 Participants programmes

The French results show, figures 30 and 31, that the specimens made of the 7050 and the 7075 alloys behave nominally equivalent under both spectra, except for the high MINI-TWIST III stress level. Under both spectra the 2024 specimens have an equal or better performance at the two lower stress levels whilst a worse performance is found at the highest stress level. This difference in behaviour of the two aluminium alloy series was also found in the low load transfer joints programme.

The results of two double shear designs, having a load transfer of about 20 % and 50 %, confirm the often observed behaviour that "lower load transfer gives higher lives". The high load transfer joints also show that cold work, in combination with clearance fit, is superior to a medium interference fit and, except at the highest stress level, to a high interference fit. But the British results show that the (split sleeve) cold work results fall, at both stress levels, in between the results of the high interference system (Hi-tigue and Taperlok) in such a way that the scatter bands overlap. This overlapping of the scatter bands prevents the making of a straight forward comparison and ranking of the fastener systems. Nevertheless, the UK results further suggest that, certainly at high stress levels, cold work in combination with a medium to high interference, as with the Huck-EXL, might have very good fatigue characteristics. Noteworthy is the effect of clamping in clearance fit system: this might give life improvements, as compared to the Hi-lok system, comparable with those gained using e.g. the Acres cold work and Hi-tigue high interference systems. One problem might be the relaxation of clamping during the life.

8.6.2 Core programme

Using the high load transfer (type D) double shear joint it is shown that FKFS-K (cold-work and medium interference) is superior to FKFS-A (clearance fit), whilst the French high interference system, in its turn, gives significantly longer lives than FKFS-K. This also points to the conclusion of 8.6.1 that cold work need to be combined with medium to high interference fit fasteners.
The correlation with the load transfer values will be made in 8.7.2.

The first observation is that scatter in single shear joints fatigue lives tends to be smaller than in double shear joints. This is because the secondary bending focussed the peak stress at the outer surface of the joint. The single shear fasteners tilt in clearance fit holes, thus having a smaller bearing areas than in double shear joints. This factor, together with the fact that single shear joints have only one mating surface for load transfer by frictional forces, also cause differences in load transfer between single and double shear joints.

Figure 35 shows that there is no single slope for the two 2000 series alloys in the life-stress plot; the same applies for the two 7000 series alloys. At higher stress levels the 2214 alloy gives longer lives than the 2024 alloy specimen, and the 7475 alloy gives shorter lives then the 7050 alloy specimen.

The investigation into rivet type, rivet material and sheet thickness (figure 37) shows that in the thicker material in particular the application of the 7050 rivet gives a large increase in life compared to the 2024 rivet; this is most striking for the Brilea rivets. However, the 7050 Brilea rivets shows the same fatigue characteristics as the standard countersunk rivet whilst the 2024 Brilea rivet is certainly not better then the 2024 countersink one. This results suggest no superior behaviour for the Brilee rivet under the simulated condition.

The few results on the comparison of the slight press fit Hi-lok and the interference fit Sleevbolt (figure 38) show no differences in fatigue life when used in 1½ dogbone specimen. Moreover, the results of these fastener systems fall in the scatterband of FKFS-A and -K results, which almost coincide. Thus different fastener systems tend to give comparable lives in 1½ dogbone specimens.

8.7.2 Core programme

As pointed out in 3.4.2 all specimens, i.e. all single shear and their double shear equivalent designs, were manufactured from one material and provided with one type of surface treatment. One half of the specimens were installed with fastener system A (FRFS-A), which has a countersunk Hi-lok installed with clearance fit in a reamed hole. The other half was installed with FRFS-B: a countersunk Hi-lok installed with interference fit in a split sleeve cold worked and reamed hole.

This section analyses the results from this and the double shear core programme.
The multiple linear regression analysis was performed on the single shear data, except for the X joint data. The equation which best fits the data is given as:

$$N = 10 \wedge (5.874 - (0.006507) * \text{stress} - (0.00994) * \text{secondary bending} + (0.009874) * \text{load transfer}. \qquad (8.4)$$

The coefficients of the secondary bending and load transfer are approximately 0.01, indicating that a 100 percent value of either secondary bending or load transfer will result in a change in life of a factor near ten. According to this equation, secondary bending results in a decrease in life and load transfer results in an increase. It is noted that the analysis treats the secondary bending and load transfer as independent variables, but they are not in actual joints.
It was thought that it may be possible to superimpose the secondary bending stress onto the applied stress. This was done for the single shear specimens by multiplying the applied stress by a factor of (1 + secondary bending/100). The resultant relationship is:

$$N = 10 \wedge (5.3822 - (0.003699) * (\text{stress} * (1 + \text{secondary bending}/100)) + (0.002200) * \text{Load transfer}) \qquad (8.5)$$

This statistical correlation resulted in approximately the same coefficient of correlation as that of eq. 8.4 but the load transfer coefficient is significantly lower. Apparently the expansion of the stress scale with the addition of the secondary bending lets the load transfer take on a different level of importance within the multiple linear regression. The degree of correlation in the equation indicates that secondary bending is a primary component in the fatigue behaviour of single shear specimens.

Figure 58 presents the fatigue test results of the core programme single shear, double shear equivalent and double shear designs. This figure also gives a regression line using equation 8.4, as an example.

The differences in life for single shear specimens with FRFS-A and with FRFS-B are small; in general, FRFS-B gives only a small improvement in life. There are three exceptions: the X joint, where there is a significant difference between the fatigue lives obtained with FRFS-A and FRFS-B (the FRFS-A series had slightly oversized holes, the FRFS-B series had very much oversized holes resulting in an average of 9 μm clearance instead of 25 μm interference), the Q joint, where there is no significant difference between the two fastener systems, thus illustrating that the increase in bending when going from FRFS-A to FRFS-B is in balance with the decrease in load transfer (table 13) and the C2 lap joint where the deviating correlation between fatigue life and stress level might be influenced by the bending restraint, preventing rotation and thus high secondary bending of the specimen at low loads and allowing rotation and thus high secondary bending (SB >> 1.00) at the high stress level. The bending restraint was not used during the secondary bending and load transfer measurements. Consequently, the secondary bending value should not be used in the evaluation of the fatigue test results.

The small differences in fatigue lives under FRFS-A and -B allow a combined plot of fatigue life versus secondary bending to be made (figure 59). Excluding the C2 lap joint result for reasons mentioned previously, a correlation is found between secondary bending, fatigue life and stress level: when increasing the stress level a reduction in life is found, but this reduction in life becomes more pronounced with increasing secondary bending. In conclusion, the beneficial effect of fatigue rated fastener systems is overshadowed by secondary bending of single shear joints. Load transfer plays a secondary rôle in this.

The double shear core programme results (figure 58) show, contrary to the single shear designs, a large life improvement when applying FRFS-B. It is noted that the results of the 1½ dogbone double shear specimens with FRFS-B are an underestimate since two tests were stopped at about 100.000 flights and a third test was stopped due to test machine malfunctioning.
This programme part also shows that the statement "the higher the load transfer, the shorter the fatigue life" could not be confirmed for all joints. It might be that small differences in the fit disturb the rating of joints on the basis of load transfer.

Comparison of the fatigue lives of single shear specimens and their double shear equivalent designs is only possible with the type C lap joint and the 1½ dogbone specimen. The first type has much shorter lives for the single shear design. It is noted that the FRFS-A double shear equivalent specimen has a lower load transfer than its single shear counterpart. The double shear equivalent design of the 1½ dogbone has longer lives only for FRFS-B. Fastener system A in the double shear equivalent design shows a somewhat smaller fatigue life than the 1½ dogbone results; this is caused by the increase in load transfer in combination with a moderate fastener system quality when changing from a single shear to a double shear joint. It is noted that the French core programme specimens had only epoxy paint as interlay surface treatment.

8.8 Correlation of fatigue lives and cost of fastener systems

For reasons mentioned in 7.4 only the total direct costs, i.e. the fastener purchase cost (based on 25000 pieces) and the manhours for hole manufacturing and fastener installation, can be evaluated in more detail. The cost/life plots (figures 60, 61) show envelopes, the cost scale of which is affected strongly by the Taperlok system. If this system is omitted a general trend of better fatigue performance with increasing cost is observed in the high load transfer data. Exceptions to this trend are the Huck-EXL, which is more cost effective, and the Acres sleeve cold-working, which is somewhat less cost effective.

These conclusions relate to specific installation requirements, e.g. fit specimen design, etc. The cost correlation with low load transfer joint result is given in figure 62. For reasons given in 7.4 the results of different participants should not be correlated. Again, the cost effectiveness of some fatigue enhancement fastener system is difficult to deduce.

9. DISCUSSION

As mentioned in chapter 2 the report the primary objectives of the FRFS programme were:

1. to determine the fatigue lives for a range of fatigue rated fastener systems in different materials in combination with hole preparation techniques and installation parameters;
2. to establish the cost figures of the fastener system in relation to the fatigue performance;
3. to identify the prime parameters involved in fastener system selection;
4. to generate design data for a number of fastener systems;
5. to develop a reference datum for the comparison of test results produced in different countries using different specimen geometries;
6. to develop experimental methods for fastener system fatigue rating.

Each of the objectives will be discussed.

9.1 Determination of the fatigue lives

Between seven- and eight hundred specimens were fatigue tested in the framework of this programme. A minor part of the programme dealt with riveted lap joints. The fasteners ranged from standard bolt to tapered fasteners installed in holes, which were drilled, reamed or coldworked. The effect of the fit of the fastener system, being a primary installation parameter, was evaluated in detail. The sheet materials used were from the 2000- and 7000-aluminium alloy series; the surface treatment, i.e. anodise, primer, sealant, etc. was applied per the participant's standard. The majority of the tests were carried out under FALSTAFF loading. In short: the first objective of the programme has been achieved.

9.2 Evaluation of the fastener system cost figures

The analysis (section 8.8) showed that the cost data of different participants could not be compared directly. However, the very detailed data of some participants give a clear insight into the cost elements of the different installation operations.
The cold-working process results in longer installation times as compared to the "ordinary" fastener systems; in particular "post cold work" steps contribute to the extra time required, but it is understood that new developments will eliminate the reaming-to-size operation. The relatively long installation time of the Taperlok is the most striking observation.
A general trend was observed when comparing the total direct installation costs with the fatigue lives obtained: increasing costs might result in a better fatigue performance. This was more marked where the potential for improvement is greatest i.e. the high load transfer double shear joints. Since moderate to high secondary bending tends to nullity the beneficial effect of fatigue enhancement fastener systems it seems not worthwhile to spend the extra costs of these systems.
A better insight into the cost effectiveness for high load transfer double shear and low load transfer joints is obtained by comparing the ratio of total direct cost and the number of flights to failure for the various fastener systems. The figures 62 and 63 present these ratios for the fastener systems evaluated by the UK. The comparison of the ratios of the high load transfer double shear joint suggests that the Huck-EXL system is the most cost effective system of the ones evaluated. Moderately cost effective are the Huckcrimp and the Split Sleeve cold work systems and -to a somewhat lesser extend- the Hi-tigue system. The Acres cold work and especially the Taperlok system are highly cost ineffective; the latter applies also for the Hi-lok installed in clearance fit in combination with high load levels.
The low load transfer joint results (figure 63) show that again the Huck-EXL is the most cost effective system. But, contrary to the double shear joint results, the Hi-tigue system is only somewhat less cost effective; the Huckcrimp system is as cost ineffective as the Taperlok system.
Care should be taken when trying to establish the potential cost benefits or penalties in practical situations.
It can be concluded that the second objective proved to be difficult to fulfil entirely. Nevertheless, the combination of cost and fatigue data given, together with above evaluation, will prove useful in the fastener system selection process.

9.3 Prime parameters in fastener system selection

The results of the correlation analyses suggest that the selection of the prime parameters should be achieved by joint geometry classification. Parameters describing the joint geometry are the secondary bending, load transfer and their dependence on the applied load.

These parameters are material dependent in low load transfer joints. For other joint types the effect of the material on the secondary bending, etc. was not established.

Load transfer plays a secondary rôle in the fatigue performance of simple shear joints. In the double shear (core) programme, differences in fastener system, in terms of life improvement, are clearly shown. Thus, load transfer is not as dominant as is the secondary bending in simple shear joints. Further, the fatigue life rating of the different designs does not correspond with the load transfer values measured in the core programme. This might be caused by the differences in interfay surface treatment (French specimen) and differences in fit as applied by the different participants. Considering other data it is concluded that fastener installation parameters (fit, clamping, cold work) and load transfer are also important parameters. It is suggested that hole manufacturing to size and fastener installation should be done at a single source for this kind of core programme.

Thus, fastener interference is a prime parameter, except when applied in single shear joints. However, no optimum value can be given. Results suggest that the interference should be at least 1 % of the fastener diameter. But with high load transfer in combination with high fatigue stress levels the cold work plus high interference is the prime parameter.

Last but not least: the cost of the fastener system, of course, is also a prime parameter. In conclusion: the FRFS programme not only identified the prime parameters in fastener system selection but also qualitatively evaluated them.

9.4 Design data

The large number of specimens tested and the numerous variables included in the programme yielded in a large amount of variable design data. It will be clear that the programme did not cover all variables, simply because the total programme was built around the various participant's individual choice of programmes.

9.5 Reference datum

The core programmes allowed a comparison of different joint geometries from various participants. Not only the fatigue tests, but in particular the determination of secondary bending, load transfer and fit contributed largely to the understanding of the behaviour of complex joints. The information obtained might serve as a good reference datum for comparison of test results to be produced in future. Moreover, the core programme results are a first step towards the definition of standard specimen for the evaluation of fatigue rated fastener systems, which will be a new AGARD SMP activity.

9.6 Experimental methods

Each participant used his own experimental techniques. The report focused on the clamping procedures of "clamping sensitive" joints as the reverse double dogbone and 1½ dogbone. Clamping sensitivity may occur when a joint does not transfer all loads from one base sheet to one other base sheet.

Experimental methods were developed with regard only to the measurement of secondary bending and load transfer. However, the pre-loading procedure should be specified exactly. The following preloading is proposed:

- 0 load → 100 % FALSTAFF → Min. load FALSTAFF → 0
- 5000 cycles: 0 load → 50 % FALSTAFF → 0
- 0 load → 100 % FALSTAFF → Min. load FALSTAFF → 0
- 5000 cycles: 0 load → 50 % FALSTAFF → 0
- 0 load → 100 % FALSTAFF → Min. load FALSTAFF → 0; at the 100 % FALSTAFF the measurements should be made.

Further, the form to record standard test information was not used widely in the programme. This is in contrast with the success of the form to record the measured fit. The procedures to measure the fit worked well.

10. CONCLUSIONS

The AGARD coordinated Fatigue Rated Fastener Systems programme has demonstrated that:

(1) Secondary bending proved to be a prime parameter. At moderate to high values it tends to nullify the beneficial effect of fatigue enhancement fastener systems; the fastener installation parameters (fit, clamping and cold work) are no prime parameters in that situation.
(2) Single shear joints are the most severely loaded joints with regard to fatigue.
(3) When secondary bending is present the load transfer plays a secondary rôle.
(4) At low to moderate secondary bending or at the absence of it the fit, clamping and cold work are prime parameters. At high load transfer and at high fatigue load levels the best results are obtained with cold worked holes plus high interference fit fasteners.
(5) Double shear joints clearly show a fastener system rating under realistic fatigue loading: the life improvement mechanisms are more marked in these joints than in low load transfer/low secondary bending joints.
(6) The low load transfer joints and the high load transfer double shear joint are not equivalent with regard to the fastener system rating and cost effectiveness.
(7) Results suggest that the effect of stress level is the same for no load and low load transfer joints; the low load transfer joint has somewhat shorter lives.
(8) The hole quality as such is not a prime parameter. However, dimensioning to size to obtain a close tolerance fit results in holes with good fatigue quality.

(9) Increasing costs of the fastener system might result in a better fatigue performance, but
- moderate to high secondary bending tends to nullify the extra costs of fatigue enhancement fastener systems;
- both in high load transfer double shear and in low load transfer joints the Huck-EXL system is the most cost effective and the Taperlok the most cost ineffective of the systems evaluated. The Huck-crimp system is moderately cost effective for the double shear joints and as cost effective as the Taperlok system in low load transfer joints; while the opposite applies for the Acres cold work system.

  The Split Sleeve cold work system is moderately cost effective for both types of joints, but it is understood that new developments will eliminate the time consuming, and thus costly, reaming to size operation. The clearance fit Hi-lok system is cost ineffective particularly at high load transfer in combination with high fatigue load levels;
- care should be taken when trying to establish the potential cost benefits or penalties in practical situations.

(10) Valuable results and, a large amount of design data were generated in international cooperation by combining participants programmes and adding core programmes.

(11) The results of the core programmes provide an excellent basis for the comparison of test results produced using different specimens.

(12) The core programme results are a first step towards the definition of standard specimens; the low load transfer core programme showed that the use of standard or reference specimen results in easily comparable fatigue test data.

(13) Standardized fatigue test spectra are undispensable.

(14) Fatigue tests on fastened joints should be accompanied by the determination of secondary bending and load transfer on each combination of specimen type, material and fastener system.

(15) The requirements and standard instrumentation for the determination of secondary bending and load transfer need only to be adjusted -as proposed- with regard to the pre-loading procedure.

(16) The diameters of each hole and fastener should be measured in fatigue test programmes, which evaluate bolted joints. The procedures adopted in this programme worked well.

11. REFERENCES

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TABLE 1
Participants of the Fatigue Rated Fastener System programme

COUNTRY	CODE	PARTICIPANTS	
FRANCE	F	Centre d'Essais Aeronautique de Toulouse-CEAT	J.P. Herteman
GERMANY	FRG	Vereinigte Flugtechnische Werke VFW-MBB	K. Hoffer
ITALY	I	University of Pisa	G. Cavallini
THE NETHERLANDS	NL	National Aerospace Laboratory-NLR	H.H. van der Linden
SWEDEN	S	SAAB-SCANIA	L. Jarfall
UNITED KINGDOM	UK	Royal Aircraft Establishment	R. Cook
UNITED STATES OF AMERICA	USA	Air Force Materials Laboratory	R.B. Urzi
		Air Force Flight Dynamics Laboratory	J.M. Potter

TABLE 2
Fatigue Rated Fastener System programme parts

JOINT DESIGNS AND EXAMPLE	PARTICIPANTS PROGRAMMES	CORE PROGRAMMES
NO LOAD TRANSFER 	F S	F S
LOW LOAD TRANSFER  RDO	F FRG I NL UK USA	UK
H.L.T. DOUBLE SHEAR 	F S NL UK	F S NL
H.L.T. SINGLE SHEAR  1½ DOGBONE	F S NL USA	F S NL UK USA

.... : for codes see table 1

TABLE 3
No load transfer joints programme

		PARTICIPANT F		PARTICIPANT S	CORE PROGRAMME
MATERIAL	2024-T3			•	
	2024-T351	•	•		o
	2214-T651	•			
	7475-T7351	•			
	7050-T7651	•			
FAYING SURFACE	ANODIZING, PAINT AND SEALANT	•			
	BARE		•	•	o
HOLE QUALITY	BROACH	•	•		o
	REAM			•	o
FASTENER	LOCKBOLT, CSK	•	•		
	BOLT, CSK, HEX.			•	o
	RIVET, CSK, UN.			•	
FIT	TRANSITION			•	o
	INTERFERENCE	•	•		o
SPECTRUM	FALSTAFF	•	•	•	o

TABLE 4
Low load transfer joints programme

		PARTICIPANTS F		FRG		I		NL			UK				core	USA
MATERIAL	2024-T3	o	o	o		o	o			o						o
	7010-T76										o	o	o	o	o	
	7050-T76	o	o	o	o			o	o							
FAYING SURFACE	ANODIZE etc.	o		o	o	o	o			o	o	o	o	o	o	
	PRIMER	o		o	o	o	o	o	o	o	o	o	o	o	o	
	SEALANT	o		o	o	o	o	o	o	o	o	o	o	o	o	
HOLE QUALITY	DRILL								o							
	DM DRILL			o	o			o		o						
	REAM		o	o		o	o				o	o		o		
	BROACH	o														
	COLD WORK						o						o		o	
FASTENER	HI-LOK		o	o		o		o	o	o	o		o	o	o	
	LOCKBOLT	o			o											
	TAPERLOK				o							o				
	HI-TIGUE											o				
	HUCKCRIMP										o					
	HUCK EXL											o				
	RIVET															o
	BOLT						o									
FIT	CLEARANCE			o			o		o		o			o		
	INTERFERENCE	o	o	o	o	o		o		o		o				o
	TRANSITION												o		o	
SPECTRUM	FALSTAFF	o		o	o	o	o	o	o		o	o	o	o	o	o
	MINI-TWIST		o					o	o	o						

TABLE 5
Double shear joints programme

DESIGN		PARTICIPANTS									
		F	NL				S		UK		
		[illegible]	[illegible]	[illegible]			[illegible]		[illegible]		
MATERIAL	2024-T351	•	•	•	•	•	•	•			
	7050-T7651	•									
	7175-T7351	•									
	7010-T7651								•	•	•
FAYING SURFACE	ANODIZE etc.	•	•	•	•	•			•	•	•
	PRIMER	•	•	•	•	•			•	•	•
	SEALANT		•	•	•	•			•	•	•
HOLE QUALITY	DM DRILL		•	•							
	REAM		•		•		•	•	•	•	
	BROACH	•									
	COLD WORK					•					•
FASTENER	HI-LOK	•	•	•	•	•			•		•
	TAPERLOK									•	
	HI-TIGUE									•	
	HUCK CRIMP								•		
	HUCK-EXL									•	
	RIVET						•				
	BOLT							•			
FIT	CLEARANCE					•	•		•		•
	TRANSITION							•			
	INTERFERENCE	•	•	•	•					•	
SPECTRUM	FALSTAFF	•					•	•	•	•	•
	MINI-TWIST	•	•	•	•	•					
	CONST. AMPL.	•									

TABLE 6
Single shear joints programme

DESIGN		PARTICIPANT				
		US	F	US	S	
		[illegible]	[illegible]	[illegible]	[illegible]	
MATERIAL	2024-T3	•	•	•	•	•
	2214-T3		•			
	7075-T76			•		
	7475-T7351		•			
FAYING SURFACE	CLAD	•				
	ANODIZE etc.		•	•		
	PRIMER		•	•		
	SEALANT		•			
	TOPCOAT			•		
HOLE QUALITY	DRILL	•		•		
	REAM				•	•
	BROACH		•			
FASTENER	HI-LOK			•		
	LOCKBOLT		•			
	RIVET	•			•	
	SLEEVBOLT			•		
	BOLT					•
FIT	CLEARANCE					
	TRANSITION					•
	INTERFERENCE	•	•	•	•	
SPECTRUM	FALSTAFF	•	•	•	•	•

TABLE 7
Core programme on single shear joints

MEASUREMENT OF SECONDARY BENDING AND LOAD TRANSFER

FATIGUE TESTS ON SINGLE SHEAR JOINTS AND THEIR DOUBLE SHEAR EQUIVALENT DESIGNS:

ALL SPECIMENS:
- o MATERIAL ALUMINIUM 7050-T76, t = 6 mm
- o INTERFAY: EPOXY PRIMER AND PR-1431-G SEALANT
- o TWO FASTENER SYSTEMS

FASTENER SYSTEM CODE	HOLE QUALITY	FASTENER	FIT +CLEARANCE -INTERFERENCE
A	REAM	HI-LOK HL-18-6-7 CSK ø6.35 mm	$20^{\pm 10}$
B	3 % COLD WORK AND REAM		$-25^{\pm 10}$
C OPTIONAL	REAM		$-80^{\pm 10}$ μm

TABLE 8
Mechanical properties of materials

SEQUENCE NUMBER	PARTICIPANT	ALLOY	HEAT TREATMENT	STARTING THICKNESS → FINAL THICKNESS (mm)	DIRECTION	TENSILE YIELD STRESS (MPa)	ULTIMATE STRESS (MPa)	ELONGATION %	YOUNG'S MODULUS (MPa)	REMARKS	MANUFACTURER
1	FRANCE	2024	T351	4.3 →	L	348	492	20.8			
					T	317	477	21.4			CEGEDUR
2		2024	T351	12 →	T	322	466	19			ALCOA
3		2024	T351	50 →	T	358	487	14.3			
					S	333	423	5.8			CEGEDUR
4		2214	T651	50 →	T	441	510	10			
					S	444	508	5.1			CEGEDUR
5		7050	T7651	5	T	565	592	12		AGARD MATERIAL [1]	ALCOA
6		7050	T7651	19 →	L	497	543	11			
					T	491	543	12			ALCOA
7		7075	T7351	18 →	T	425	437	12			CEGEDUR
8		7475	T7351	55 →	L	444	510	9.8			
					T	443	509	11.1			CEGEDUR
					S	417	504	7.6			
9	FED. REP.	2024	T3	5	L	351.7	470.8	20.7	68263		CEGEDUR
10	GERMANY	7050	T76	5	L	511.0	570.0	15.3	69671	AGARD MATERIAL [1]	ALCOA
11	ITALY	2024	T351	5							
12	THE	2024	T3								
13	NETHERLANDS	7050	T76							AGARD MATERIAL [1]	[illegible]
14	UK	7010	T7651	19 →	L	450	530	8			
15		7050	T76	5						AGARD MATERIAL [1]	AL
16	USA	2024	T3	3.2						CLAD	
17		2024	T351	1.6							
				2.3						CLAD	
18	[illegible]	7050	T76	5						AGARD MATERIAL [1]	ALCOA
19		7075	T76	3.2						AGARD MATERIAL [1]	ALCOA
20	SWEDEN	2024	T3	5	L	360	466	19.5	73200		
21		7010	T73651	120→8	L	431	498	12.0	70700		
22		7050	T76	5	L	532	566	15.0	76200	AGARD MATERIAL	ALCOA

[1] see reference 1

TABLE 9
Faying surface treatment

SEQUENCE NUMBER	PARTICIPANT	ANODIZING LAYER	PRIMER	TOPCOAT	SEALANT	FASTENER INSTALLATION
1	FRANCE	-	EPOXY PRIMER [illegible]	EPOXY [illegible]	-	WET
2		-	EPOXY PRIMER [illegible]	EPOXY [illegible]	-	WET
3		[illegible]	PRIMER	-	[illegible]	DRY
4		[illegible]	PRIMER	-	[illegible]	WET
5	GERMANY	ANODIZING	ZINC CHROMATE PRIMER	-	[illegible]	WET WITH [illegible]
6		ANODIZING	ZINC CHROMATE PRIMER	-	[illegible]	DRY; [illegible]
7	ITALY	ANODIZING	PRIMER	-	[illegible]	WET WITH [illegible]
8	THE NETHERLANDS	-	PRIMER	-	[illegible]	WET
9		CHROMIC ACID	ADHESIVE PRIMER [illegible]	-	[illegible]	WET
10		-	EPOXY PRIMER		[illegible]	
11	UNITED KINGDOM	[illegible]	EPOXY PRIMER		[illegible]	WET WITH [illegible]
12	USA	-	-	-	-	-
13		CHROMIC	EPOXY PRIMER	POLYURETHANE PAINT	-	-
14	[illegible]	-	EPOXY PRIMER	-	[illegible]	[illegible]
15	SWEDEN	-	EPOXY PRIMER	-	[illegible]	WET

TABLE 10
Fastener systems

SEQUENCE NUMBER	PARTICIPANT	HOLE PRODUCTION STEPS	FASTENER	FIT (µm)
1	FRANCE	REAM TO Ø 6.35 HOLE	HI-LOK Ø 6.35, Steel, CSK	CLEARANCE 10-30
2		BROACH TO Ø 6.35 HOLE	HI-LOK Ø 6.35, Ti, CSK	CLEARANCE 10-30
3		REAM (Ø 5.81-5.97) - COLD WORKING 3 % - REAM TO 6.35	HI-LOK Ø 6.35, Steel, CSK	INTERFERENCE 15-35
4		REAM (Ø 5.71-5.97) - COLD WORKING 3 % - BROACH TO 6.35	HI-LOK Ø 6.35, Ti, CSK	INTERFERENCE 15-35
5		BROACH TO Ø 6 HOLE	LOCKBOLT SL Ø 6, TAKV, CSK	INTERFERENCE 16-32
6		REAM TO Ø 6.31 HOLE	HI-LOK Ø 6.35, TAKV, Bull nose	INTERFERENCE 80
7	F.R. GERMANY	REAM TO Ø 6.30 (H7)	HI-LOK HL10VF-8-7, COLLAR HL70-8	INTERFERENCE 17
8		DOUBLE MARGIN DRILL TO Ø 6.26 (H11)	DITTO	INTERFERENCE 36
9		REAM TO Ø 6.30 (H7)	DITTO	INTERFERENCE 22
10		DOUBLE MARGIN DRILL TO Ø 6.26 (H11)	DITTO	INTERFERENCE 40
11		REAM TO Ø 6.34 AND 6.30 (H7)	DITTO	CLEARANCE 12
12		REAM TO Ø 6.29 (H7)	LOCKBOLT SALP P-T 8-07, COLLAR 6 LC-C 8	INTERFERENCE 15
13		DOUBLE MARGIN DRILL TO Ø 6.26 (H11)	DITTO	INTERFERENCE 21
14		DITTO	LOCKBOLT GPL 5 SP-OT 08-7, COLLAR 2 SCC-C-8	INTERFERENCE 42
15		TAPERLOCK REAMER (TRL 2040 BR 3-4)	TAPERLOCK TLN 200-4-4, COLLAR TLN 1010-4	INTERFERENCE 17
16	ITALY	DRILL Ø 4.5 (MANUAL) - REAM Ø 5e8 - see table 15S	HI-LOK Ø 5, Ti, CSK, SHEAR TYPE, LN 29797-05	INTERFERENCE 13-45
17		DRILL Ø 5.1 (MANUAL) - REAM Ø 6a6 - see table 15S	HI-LOK Ø 6, Ti, CSK, SHEAR TYPE, LN 29797-06	INTERFERENCE 15-43
18		DRILL Ø 5.5 (MANUAL) - REAM Ø 6a8 - see table 17S	HI-LOK Ø 6, Ti, CSK, TENSION TYPE, PAN 5215-06	INTERFERENCE 15-43
19		DRILL Ø 5.5 (MANUAL) - REAM Ø 6a6 - see table 17S	HI-LOK, Ø 6, Ti, PROTRUDING, SHEAR TYPE, LN 29796-06	INTERFERENCE 15-43
20		DRILL Ø 7.5 (MANUAL) - REAM Ø 8a8 - see table 15S	HI-LOK, Ø 8, Ti, CSK, SHEAR TYPE, LN 29797-08	INTERFERENCE 16-51
21		DRILL Ø 5.258-5.334 - SPLIT SLEEVE COLD WORK 3.51-4.83 % - REAM Ø 6H8 - see table 1CW6	STD. BOLT, Ø 6, Ti, CSK, LN 29956-06	CLEARANCE 10-40
22		REAM - see 17 -	HI-LOK, Ø 6, Ti, CSK, HSTN11-06-11 SIMILAR TO LN 29797	INTERFERENCE 13-43
23		COLD WORK, REAM - see 21 -	STD. BOLT, Ø 6, Ti, CSK, LN 29956-06	INTERFERENCE 15-45
24	THE NETHERLANDS	DOUBLE MARGIN DRILL Ø .2465" - see table 5 -	HI-LOK HL10VF-8-7, PROT.H., Ø 6.35	TRANSITION 21-76
25		STANDARD DRILL Ø 6.4 - see table 6 -	DITTO	CLEARANCE 63-255
26		DOUBLE MARGIN DRILL - see table 1 -	HI-LOK HL 19-8-7, CSK, Ø 6.35	INTERFERENCE 20-40
27		REAM - see table 7 -	DITTO	INTERFERENCE 80-100
28		COLD WORK 2.86 % - REAM - see table 7 -	DITTO	CLEARANCE 0-25
29	UK	DRILL-REAM TO Ø .2500"-.2509" (H8)-CSK-DEBURR	HI-LOK B-FAST NUT (60-80 lbs in)	
30		DRILL-TAPER REAMER	TAPERLOK	
31		DRILL-REAM TO Ø .2445"-.2460"-CSK-DEBURR	HI-TIGUE B-EAST NUT (90-100 lbs in)	
32		DRILL-REAM TO Ø .2500"-.2509" (H8)-CSK-DEBURR	HUCKCRIMP-NUT (84 lb in)	
33		DRILL/CSK TO Ø .238"-.241" USING HUCK COMBINED CUTTER-DEBURR-HUCK MANDREL COLD WORK TO Ø .244"-.249"	HUCK KEL, COLLAR WITH HUCK SWAGING TOOL	
34		DRILL-REAM TO Ø .235"-.238"-DEBURR LIGHTLY-SPLIT SLEEVE COLD WORK-REAM TO Ø .248"-.249" CSK DEBURR	HI-LOK B-FAST NUT (60-80 lb in)	
35		DRILL-REAM TO Ø .259"-.260"-CSK-DEBURR-INSERT COLD WORKING ACRES SLEEVES WET	HI-LOK B-FAST NUT (60-80 lb in)	
			29-35: TORQUE VALUE CONFIRMED AFTER 2 HOURS OF INITIAL FASTENING AND IMMEDIATELY PRIOR TO TESTING	
36	USA	STANDARD DRILL-DEBURR	SOLID RIVET (MS 20426) Ø 3/16" FLUSH HD — HAND BUCKED	1056-1
37		STANDARD DRILL-DEBURR	MACHINE SQUEEZED	2024
38		STANDARD DRILL-DEBURR Per MIL-HDBK-5, table 8.1.2 (b) .001	RIVET Ø 3/16" (MS20470) 2024-T31(DD), SQUEEZED	
39		DITTO	DITTO 7050-T73(B), -	
40		DITTO	RIVET Ø 1/4" (MS20470) 2024-T3(DD), -	
41		DITTO	DITTO 7050-T73(B), -	
42		DITTO	RIVET Ø 5/16" (MS20426) 2024-T3(DD), -	
43		DITTO	DITTO 7050-T73(B), -	
44		DITTO	RIVET Ø ¼" (MS20426) 2024-T3(DD), -	
45		DITTO	Ø ¼" (MS20426) 7050-T73(B), -	
46		DITTO	Ø ¼" [illegible] 2024-T3(DD), -	
47		DITTO	Ø ¼" [illegible] 7050-T73(B), -	
48		STEP DRILL Ø ¼ #, DRILL Ø 6.306 TO HOLE Ø 6.342-6.350	HI-LOK HL-19-PB-8 5, COLLAR HL-70-8 (LOCTP)	CONTR. SLIGHT PRESS FIT
49		REAM TO Ø .306"-.307"	SLEEVBOLT PBF SB110-6, COLLAR [illegible]	INTERFERENCE 64
50	CONS. FRANCE	FEPS-A		
51		FEPS-6		
52	SWEDEN	DRILL TO Ø 5.0-5.2, REAM TO Ø 5.965 (typ)	HI-LOK HLH-11-06 ¼"	AVE INT. 7 µm

Dimensions in mm

TABLE 11
Standard test info-‑‑tion to be recorded

FATIGUE TEST

(a) General Data
Date and location of testing
Manufacturer/model of fatigue test machine
Test temperature (°C)
Relative humidity (%).

(b) Specimen Data
Material specifications
Type of specimen, including interfay compounds, etc.
Specimen identification
Type of surface (machining history and treatment)
Fastener system: fastener type
dry/wet installed
fit
hole preparation technique
Installation costs of the fastener system.

(c) Test Data
Type of loading
Mean cyclic frequency
Frequency of maximum load excursion (for standard spectrum loading)
Characteristic stress levels (mean, or peak stress for standard spectrum loading)
Cyclic waveform
Number of cycles or flights to failure
Fracture surface observations including initiation sites.

TABLE 12
Definition of flight types and number of load cycles within each flight for TWIST and MINI-TWIST
(if different, figures between brackets refer to MINI-TWIST; otherwise MINI-TWIST equal to TWIST)

Flight type	Number of flights in one block of 4000 flights	Number of gust loads (full cycles) at the 10 amplitude levels										Total number of cycles per flight
		I	II	III	IV	V	VI	VII	VIII	IX	X	
A	1	1	1	1	4	8	18	64	112	391	900 (0)	1500 (600)
B	1		1	1	2	5	11	39	76	366 (385)	899 (0)	1400 (520)
C	3			1	1	2	7	22	61	277 (286)	879 (0)	1250 (380)
D	9				1	1	2	14	44	208	680 (0)	950 (270)
E	.					1	1	6	24	165 (168)	503 (0)	800 (200)
F	60						1	3	19	115 (107)	512 (0)	650 (150)
G	181							1	7	70 (72)	412 (0)	490 (80)
H	420								1	16	233 (23)	250 (40)
I	1090									1	69 (4)	70 (5)
J	2211										25 (2)	25 (2)
Total number of cycles per block of 4000 flights		1	2	5	18	52	152	800	4170	34800	358665 (18422)	
Cumulative number of load cycles per block of 4000 flights		1	3	8	26	78	230	1030	5200	40000	398663 (58422)	

TABLE 13
Secondary bending and load transfer of single shear core programme specimens at fatigue test stress levels

SINGLE SHEAR CORE PROGRAMME SPECIMEN	STRESS LEVEL (MPa)	FRFS-A		FRFS-B	
		SB	LT (%)	SB	LT (%)
TYPE C	150 200	1.32 1.23	54 54	1.52 1.42	41 43
TYPE Q	210 263	.42 .44	47 49	.53 .53	43 43
TYPE C2	150 200	- -	[1.08] (1) [: 07] (2)	- -	(3) 50 50
1½ DOGBONE	200 250	.04 .09	25.4 25.8	.21 .22	22.7 23.8
X JOINT	150	.80	50		(3)

SINGLE SHEAR CORE PROGRAMME SPECIMEN	STRESS LEVEL (MPa)	FRFS-A	FRFS-B
		LT (%)	LT (%)
TYPE J1 DS-JOINT	150 200 250	45.8 46.0 46.7	42.0 43.8 44.4
TYPE D DS-JOINT	200 250	33.8 33.9	41.8 41.7
1½ DS DOGBONE	200 250	35 35	41 40
DOUBLE SHEAR OF TYPE C2	150 200	- -	[47] (2) [50] (4)
TYPE M1 & M2	NOMINAL VALUE LT = 20 % (3)		
TYPE H1	NOMINAL VALUE LT = 50 % (3)		

(1) without bending restraints

(2) instrumentation not in accordance with requirements

(3) nominal value, not measured with FRFS-A, -B; measured in:
8 mm plate: SB = 0.83
4 mm plate (150 MPa): SB = 0.73   LT = 47
(50 MPa)   LT = 50

(4) side sheets t instead t/2

TABLE 14
Cost of fastener systems

PARTICIPANT	FASTENER SYSTEM	COST OF EQUIPMENT AND TOOLS ($)	① COST PER FASTENER ($)	PREPARING TIME	② INSTALLATION TIME PER FASTENER (min) * predrill up to installation	① + ② TOTAL COST PER 1000 FASTENER INSTALLATIONS ($) (7)
GERMANY	HI-LOK + DH	-	1.36	1.14 min. (1)	1.16	1723
	(GP) LOCKBOLT + DH	-	0.48 per 25000	.62 min. (1)	1.08	818
	TAPERLOK	-	1.44	2.39 min. (1)	3.18	2436
ITALY	TI HI-LOK CSK SHEAR	-	1.00		1.54	1483
	TI HI-LOK PROTR. SHEAR	-	-		1.51	1473
	TI HI-LOK CSK TENSION	-	- per 25000		1.68	1526
	CW+TI HI-LOK CSK SHEAR	-	-		2.64	1827
	CW+TI STD. BOLT CSK	-	0.64 (2)		2.78	1811
THE NETHERLANDS	HI-LOK/STD.OR DH DRILL	-	1.12 per	1.56 h (4)	3.21 (5)	2126
	HI-LOK/REAM	-	1.12 25000	1.80 h (4)	3.57 (5)	2239
	HI-LOK/CW + REAM	-	1.42 (3)	2.28 h (4)	4.29 (5)	2764
UNITED KINGDOM	HI-LOK/PLANE HOLE	1019	1.51		5.2	1683
	TAPERLOK	1080	3.48		26.0	11627
	HUCK-EXL	540	.67		7.0	2863
	HI-TIGUE	1046	1.17 per		5.5	3433
	HUCKCRIMP	587	.73 5000		7.0	2923
	HI-LOK + CW	4271	1.58 (5)		10.3	4807
	HI-LOK + ACRES CW	2098	1.89 (3)		8.3	4491
USA	HI-LOK				54 (6)	-
	SLEEVBOLT				60 (6)	-

NOTES:
(1) includes preparation of tooling, sealant and of inspection
(2) without cost of sleeve
(3) inclusive cost of sleeve
(4) indicated time is per test series
(5) inclusive sealant and primer application
(6) includes hole and fastener inspection
(7) assumed: 1 manhour = $ 18.8

TABLE 15
Relative cost of fastener system

PARTICIPANT	FASTENER SYSTEM	RELATIVE COST OF EQUIPMENT AND TOOLS	RELATIVE COST PER FASTENER	RELATIVE PREPARING TIME	RELATIVE INSTALLATION TIME PER FASTENER	RELATIVE TOTAL COST PER FASTENER INSTALLATION
GERMANY	HI-LOK + DM	-	100	100	100	100
	(GP)-LOCKBOLT + DM	-	35	54	93	47
	TAPERLOK	-	106	210	274	141
ITALY	TI HI-LOK CSK SHEAR	-	100	-	100	100
	TI HI-LOK PROTR SHEAR	-	-	-	98	99
	TI HI-LOK CSK TENSION	-	-	-	109	103
	CW+TI HI-LOK CSK SHEAR	-	-	-	171	123
	CW+TI STD BOLT CSK	-	64	-	181	122
THE NETHERLANDS	HI-LOK/STD or DM DRILL	-	100	100	100	100
	HI-LOK/REAM	-	100	115	111	105
	HI-LOK/CW + REAM	-	127	146	134	130
UNITED KINGDOM	HI-LOK/PLANE HOLE	100	100	-	100	100
	TAPERLOK	106	230	-	500	691
	HUCK-EXL	53	45	-	135	170
	HI-TIGUE	103	113	-	106	204
	HUCKCRIMP	58	48	-	135	174
	HI-LOK + CW	419	104	-	198	286
	HI-LOK + ACRES CW	206	125	-	160	267
USA	HI-LOK	-	-	-	100	-
	SLEEVBOLT	-	-	-	111	-

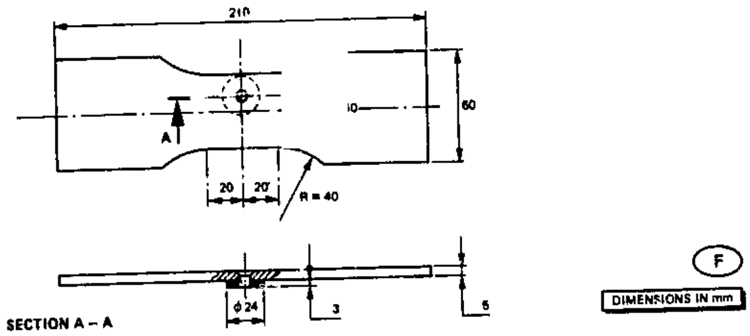


Fig. 1a No load transfer specimen - French design "B"

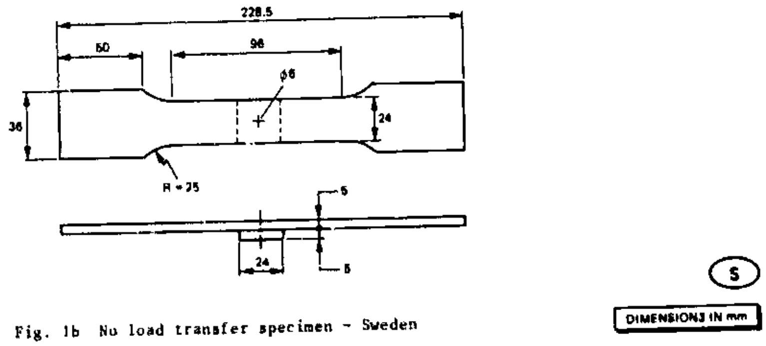


Fig. 1b No load transfer specimen - Sweden

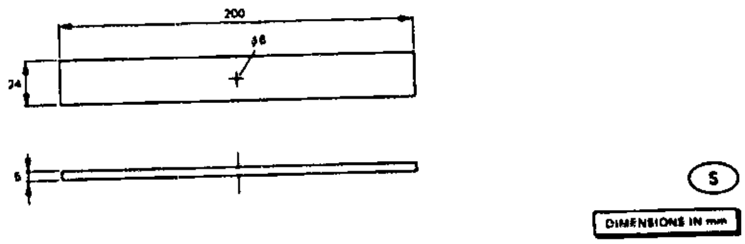


Fig. 1c No load transfer open hole specimen - Sweden

Fig. 2a AGARD low load transfer reverse double dogbone specimen

CLAMPING AREA

DIMENSIONS IN mm

Fig. 2b AGARD low load transfer reverse double dogbone specimen
(specimen configuration of FRG)

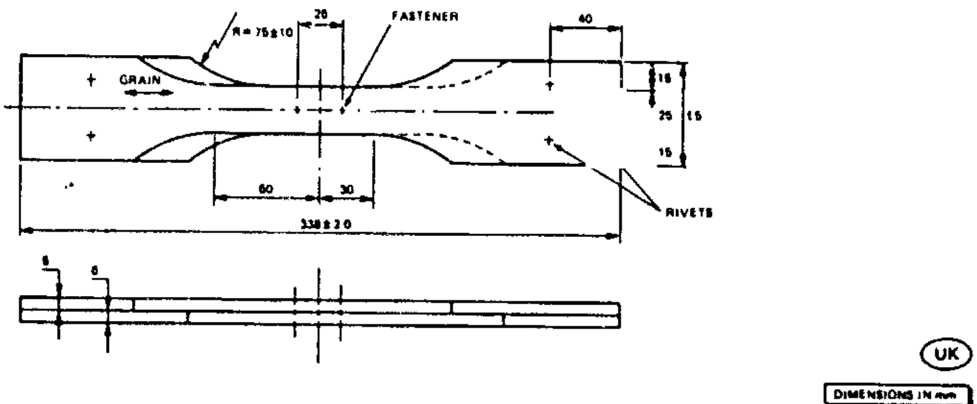


Fig. 2c UK low load transfer reverse double dogbone specimen

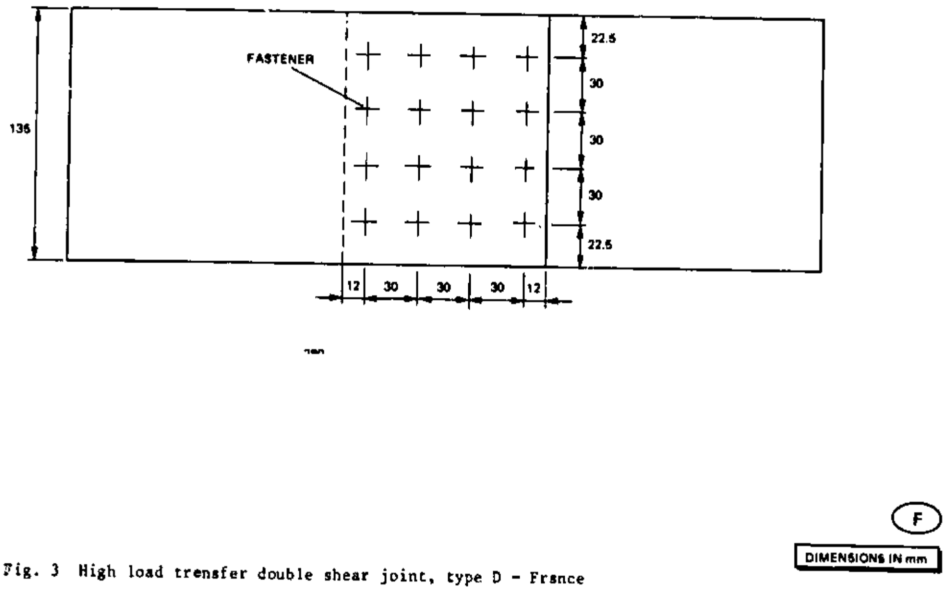


Fig. 3 High load trensfer double shear joint, type D - Frsnce

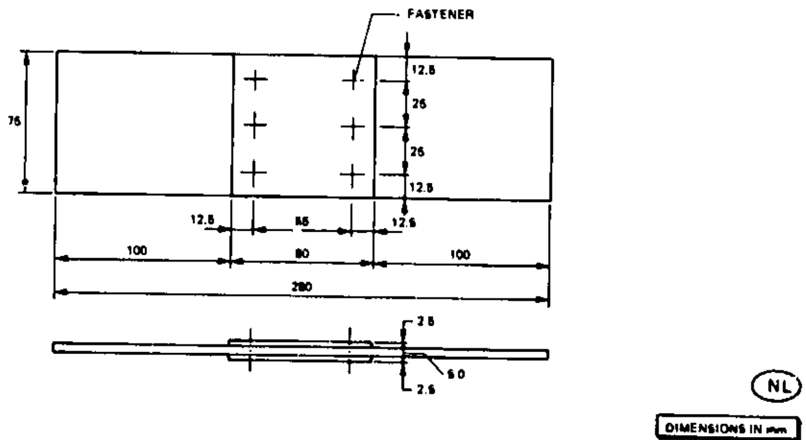


Fig. 4a Medium load transfer double shear joint, type M1 - the Netherlands

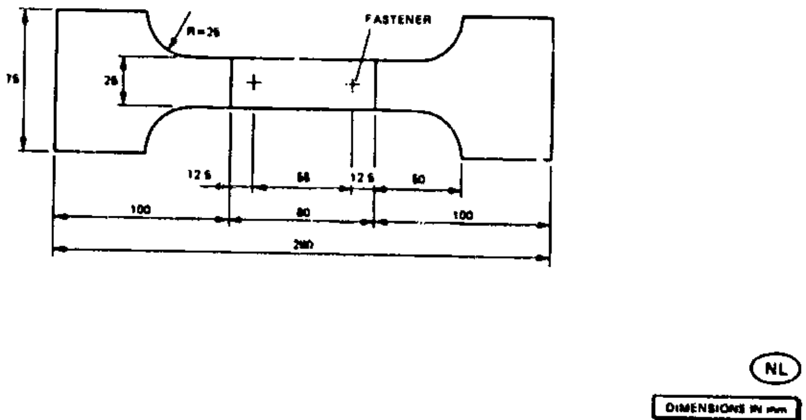


Fig. 4b Medium load transfer double shear joint, type M2 - the Netherlands

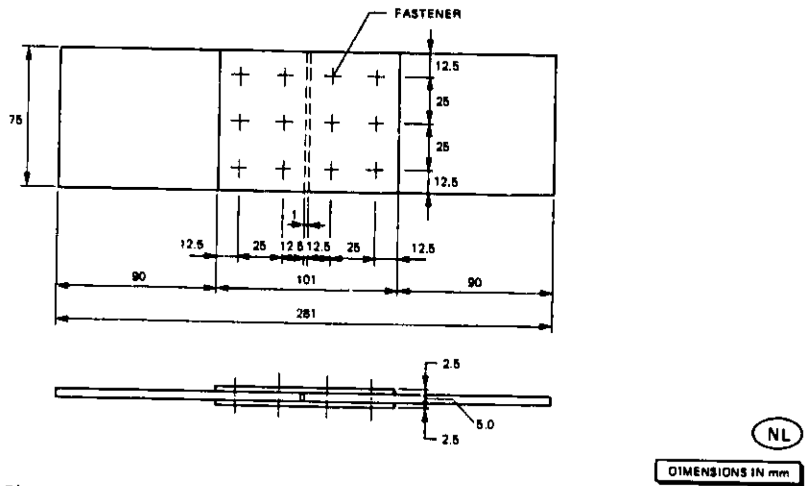


Fig. 5 High load transfer double shear joint, type H1 - the Netherlands

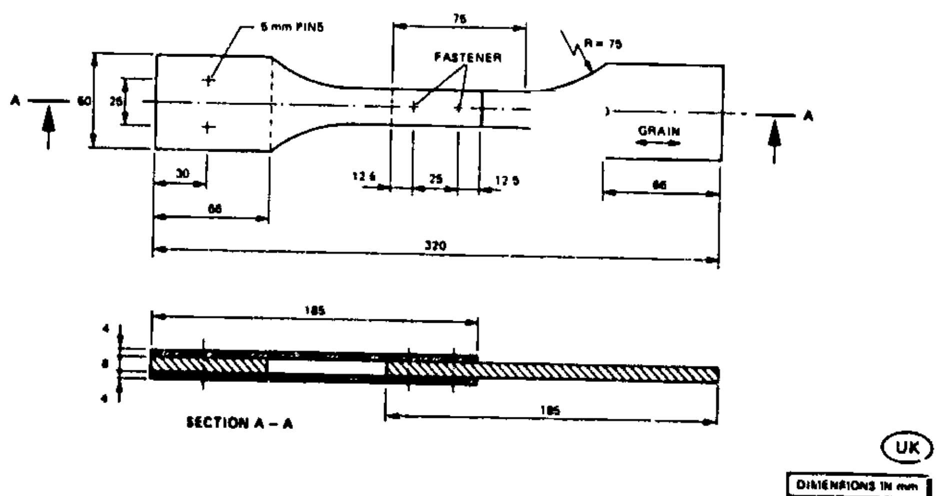


Fig. 6 High load transfer double shear joint, type H2 - United Kingdom

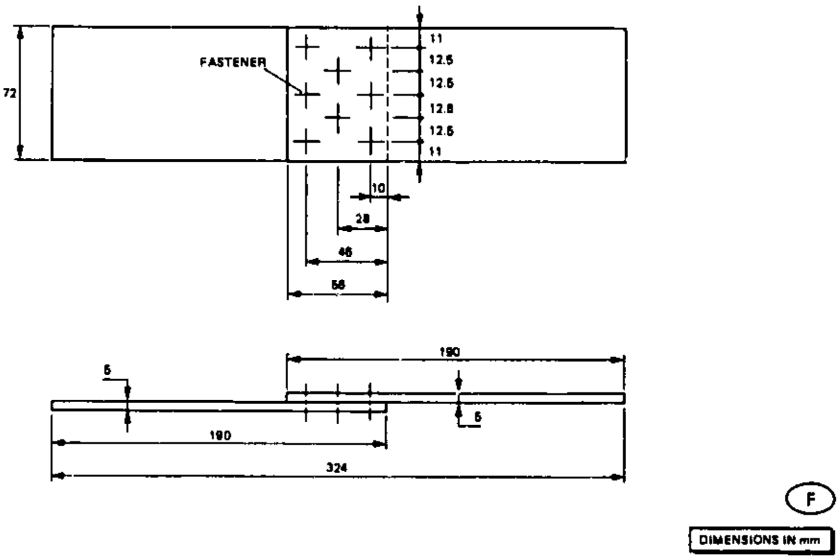


Fig. 7 High losd transfer single shesr joint, type C - Frsnce

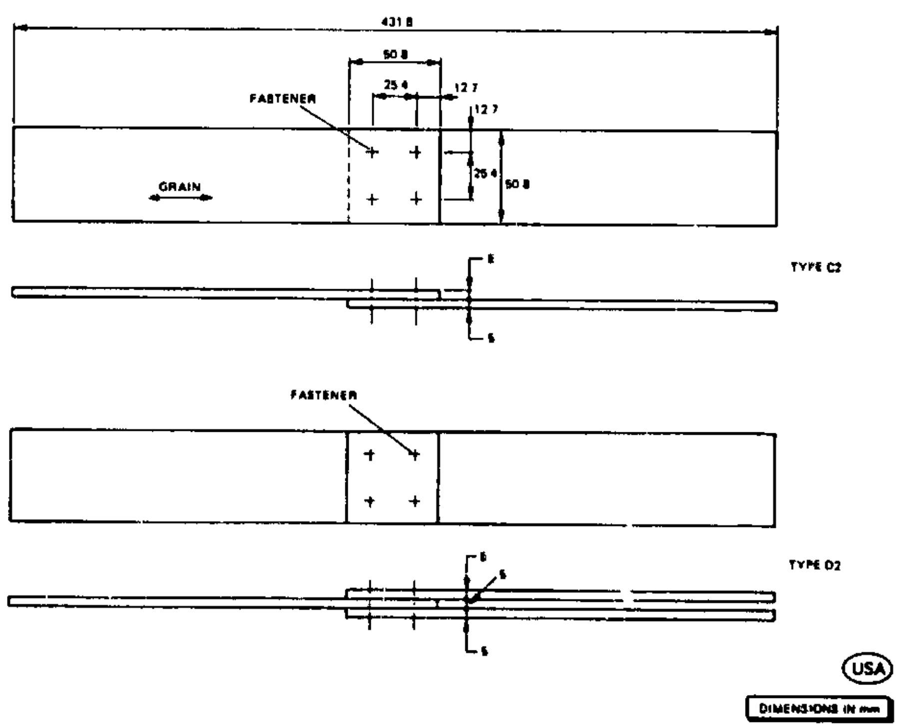


Fig. 8 High load transfer lap joint specimen, type C2, and its double shear equivalent, type D2 - USA

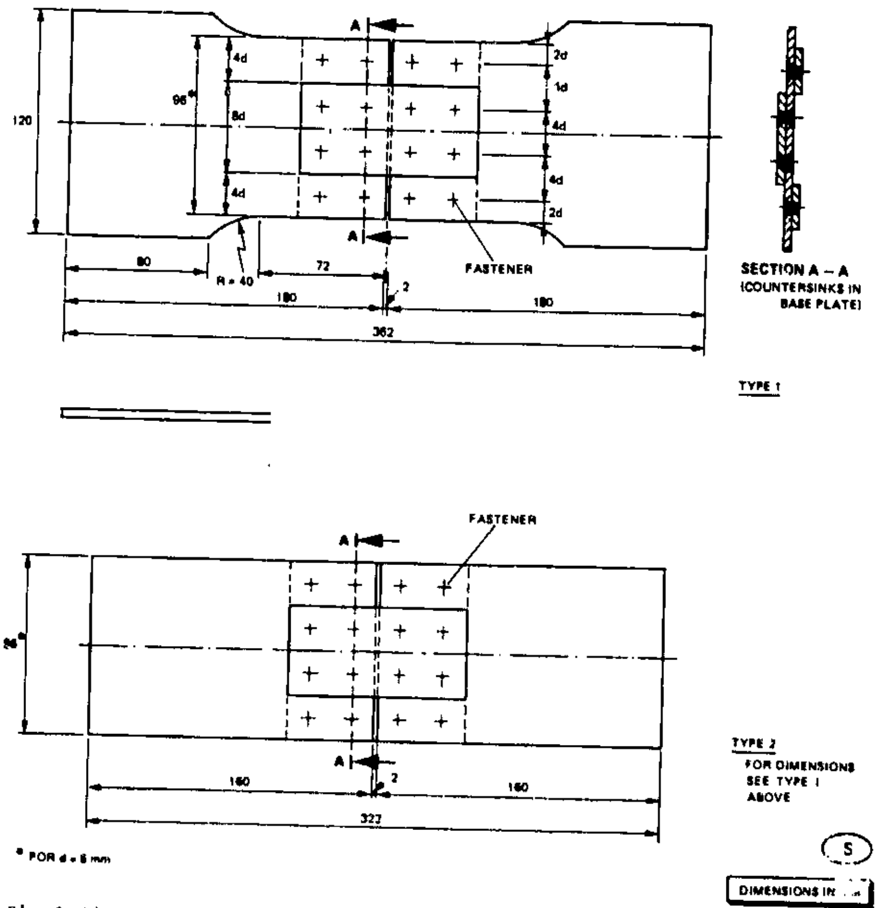


Fig. 9 High load transfer single shear X joints - Sweden

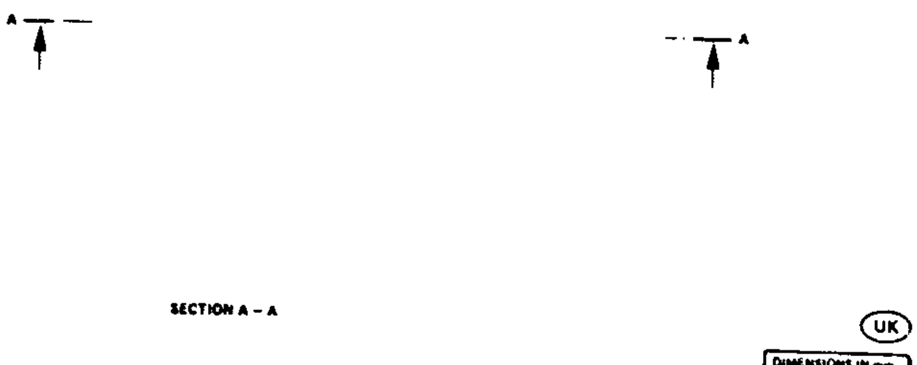


Fig. 10 High load transfer Q joint - United Kingdom

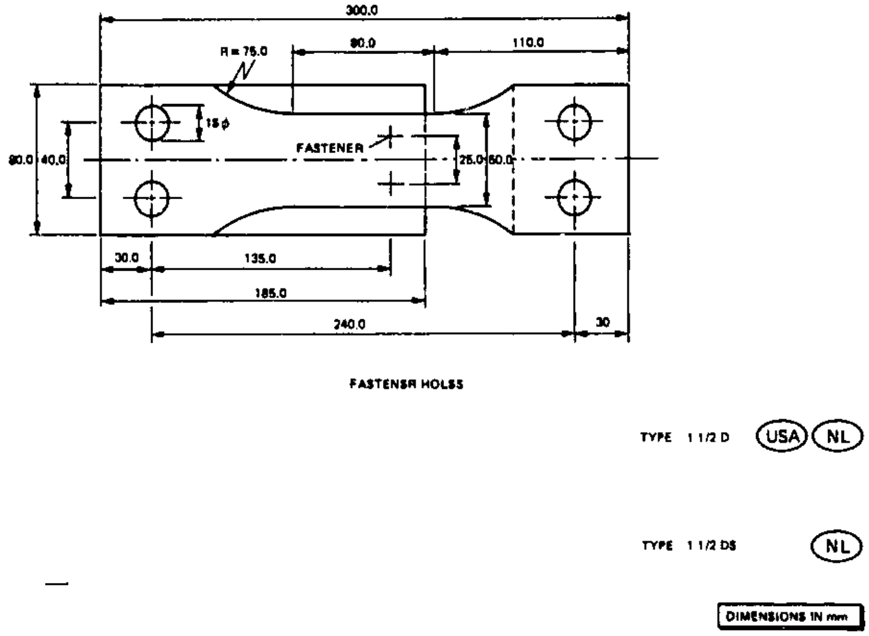


Fig. 11 The 1½-dogbone specimen, type 1½D, and its double shear equivalent design, type 1½DS - USA (1½D type) and the Netherlands (both types)

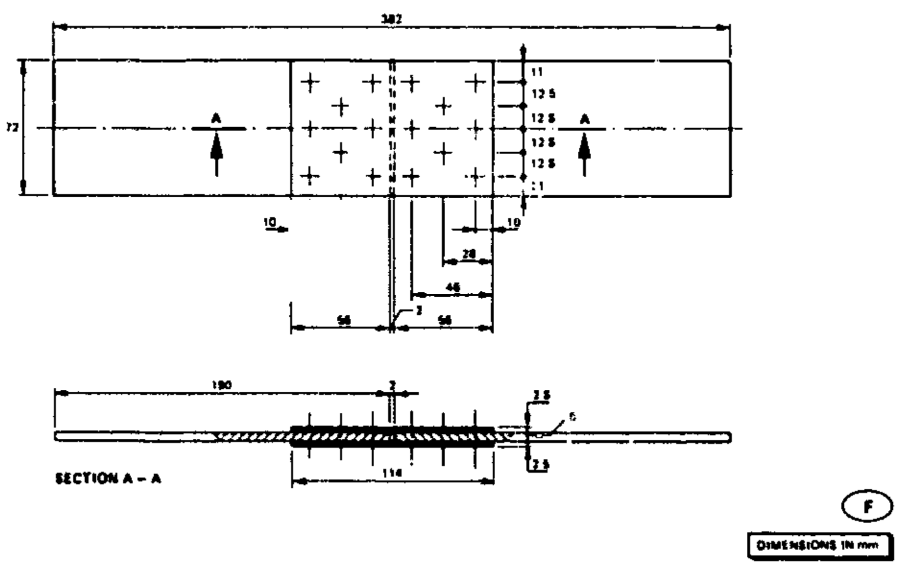


Fig. 12 High load transfer double shear joint, type CI - France

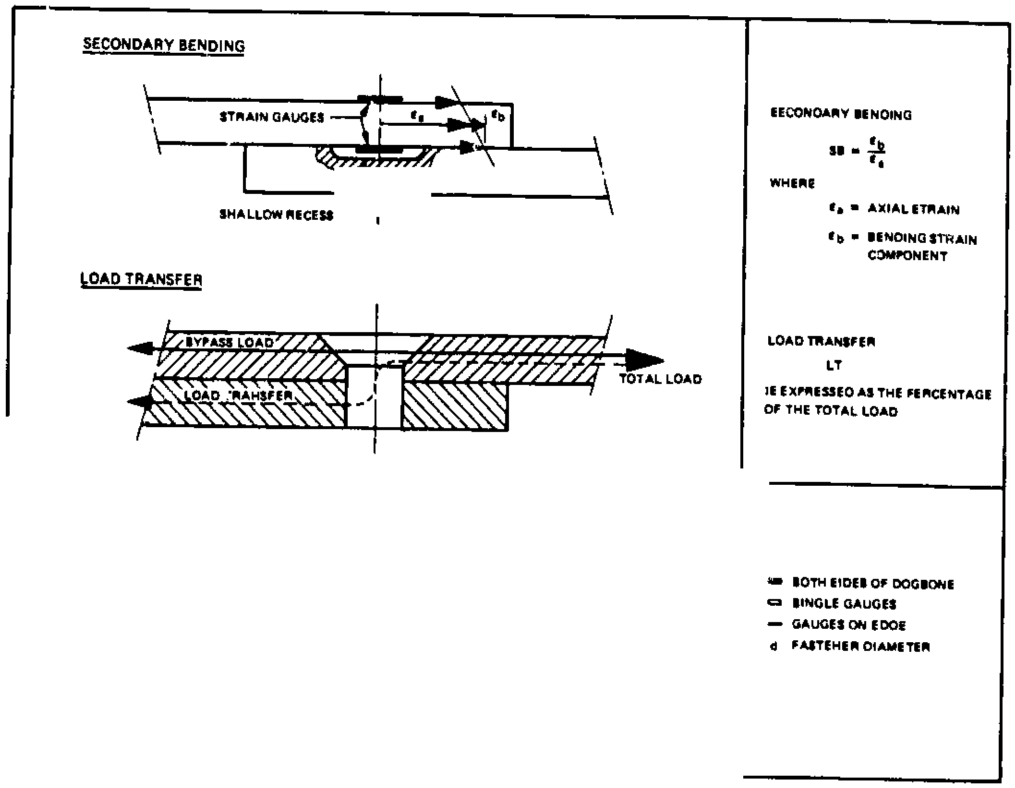


Fig. 13 Secondary bending and load transfer. Definitions and position of strain gauges

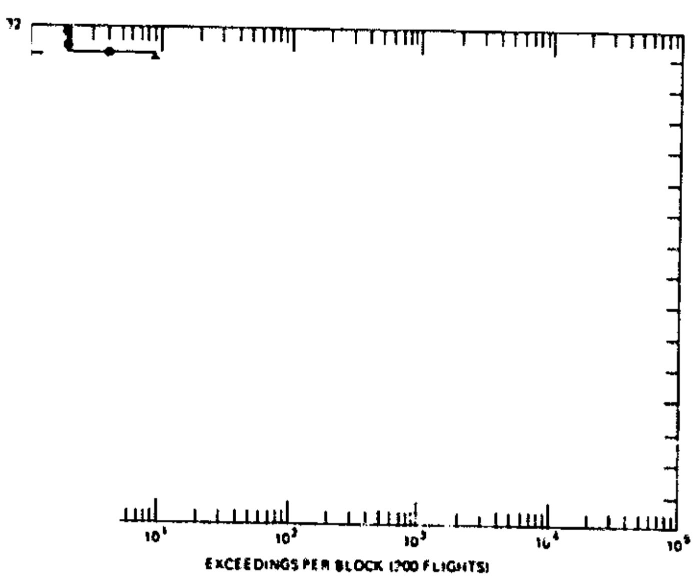


Fig. 14 FALSTAFF load spectrum

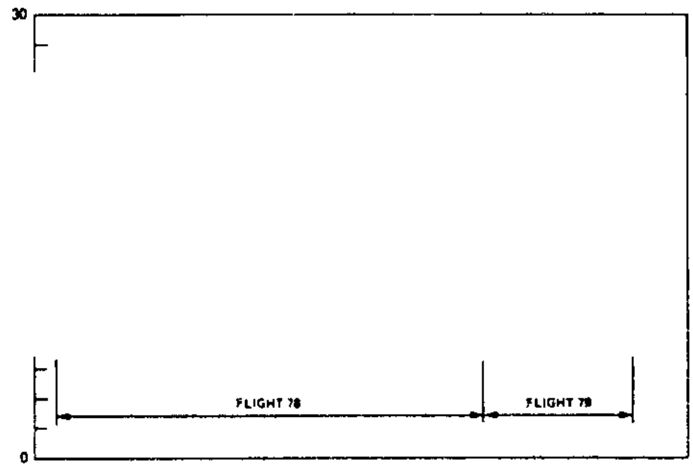


Fig. 15 Part of FALSTAFF sequence

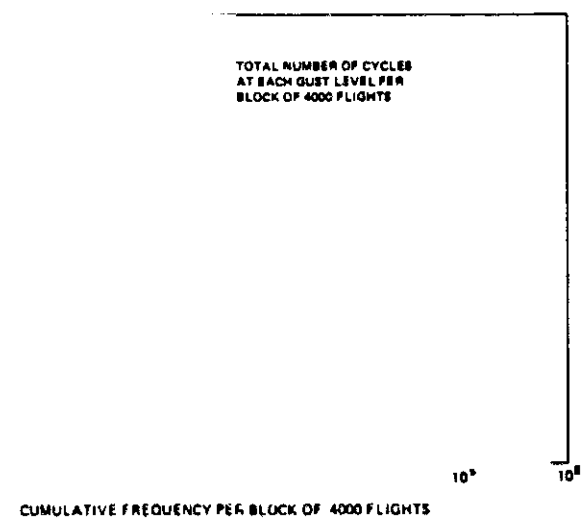


Fig. 16 The gust spectrum TWIST

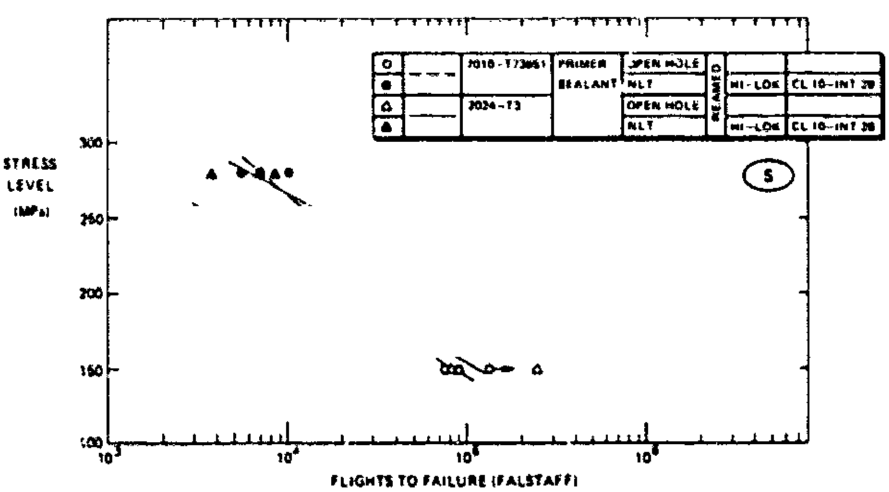


Fig. 17 Open hole specimen and no load transfer joints - Sweden

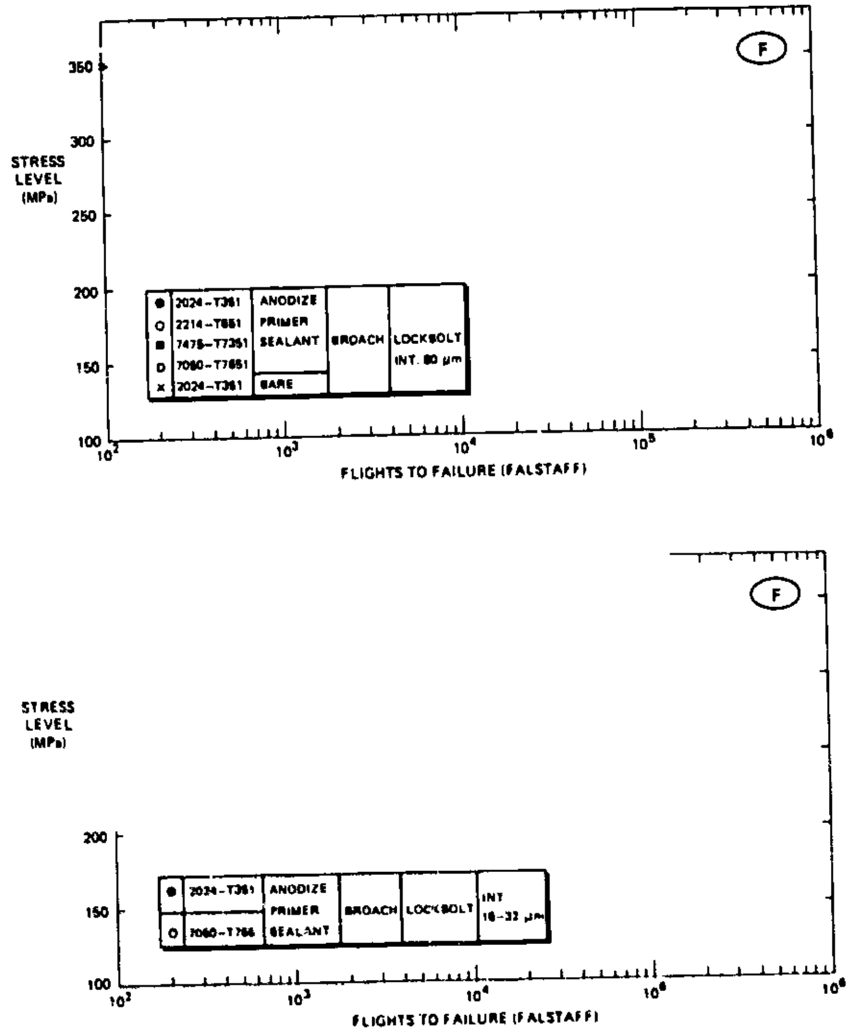


Fig. 19 Low load transfer joints - France

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 20 Low load transfer joints - France

10⁵ 10⁶

CYCLES TO FAILURE (CONSTANT AMPLITUDE)

Fig. 21 Low load transfer joints - France

10^2 10^3 10^4
FLIGHTS TO FAILURE (FALSTAFF)

Fig. 22 Low load transfer joints - Fed. Rep. of Germany

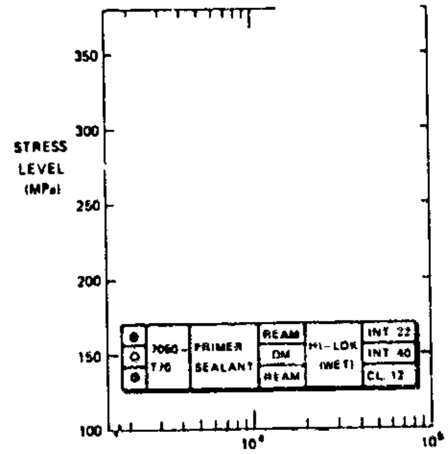


Fig. 23 Low load transfer joints - FRG

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 24 Low load transfer joints - FRG

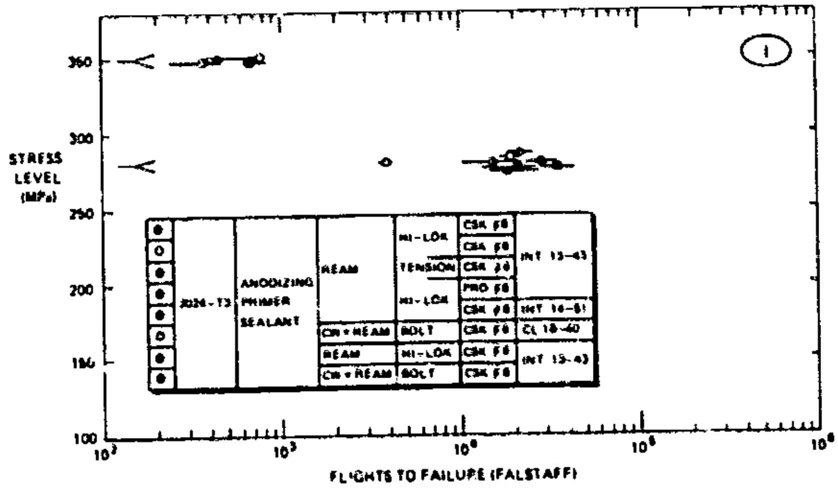


Fig. 25 Low load transfer joints - Italy

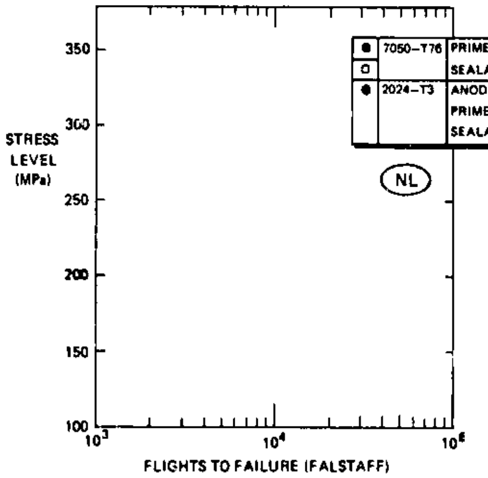


Fig. 26 Low load transfer joints - the Netherlands

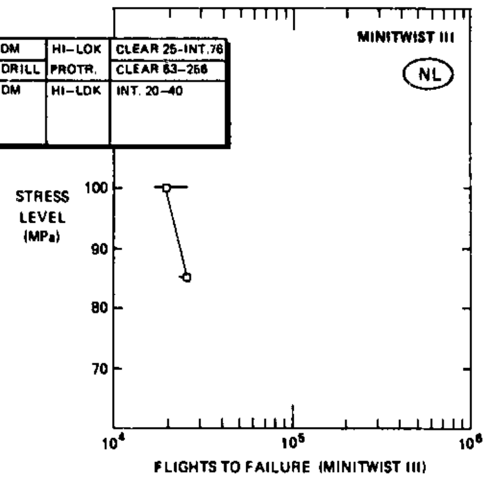


Fig. 27 Low load transfer joints - the Netherlands

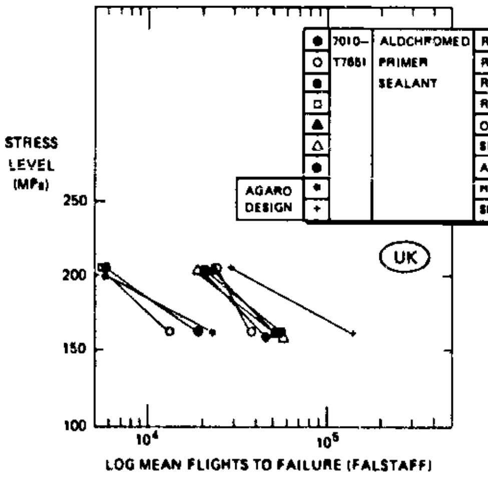


Fig. 28a Low load transfer joints - UK

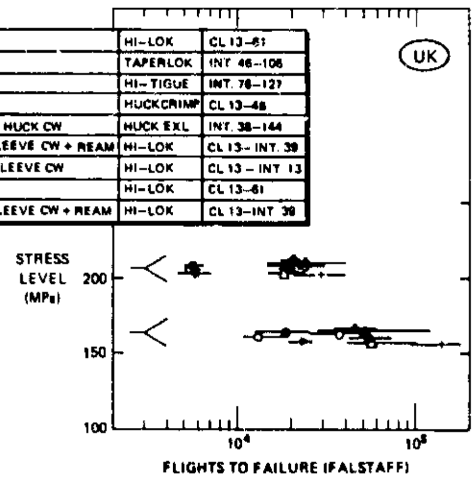


Fig. 28b Low load transfer joints - UK

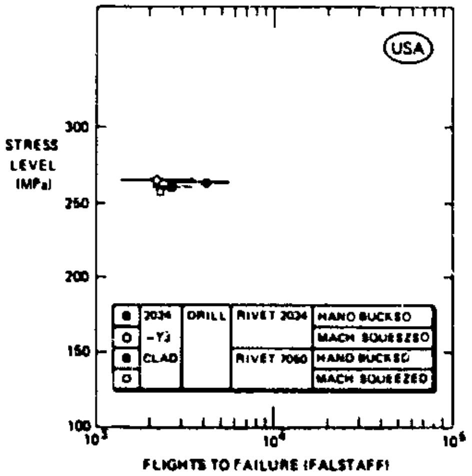


Fig. 29 Low load transfer joints - USA

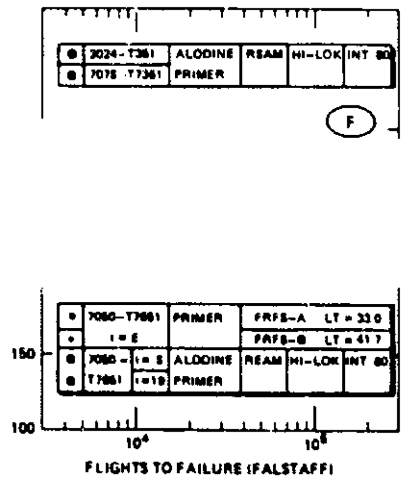


Fig. 30 Type D double shear joints - France

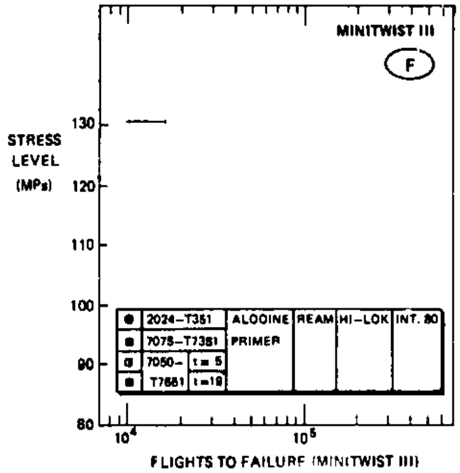


Fig. 31 Type D double shear joints - France

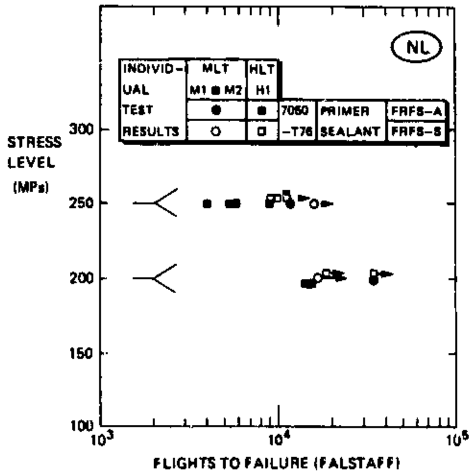


Fig. 32 Medium and high load transfer double shear joints - the Netherlands

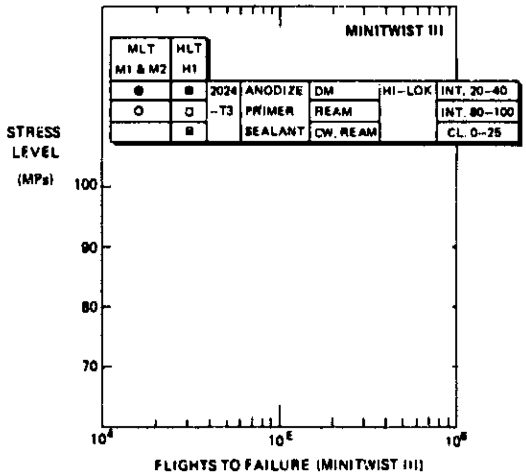


Fig. 33 Medium and high load transfer double shear joints - the Netherlands

Fig. 34 High load transfer double shear joints - United Kingdom

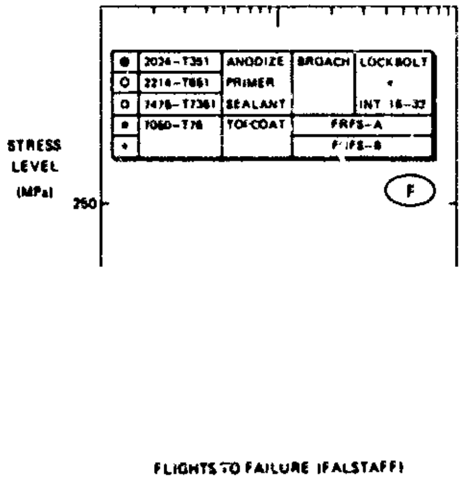


Fig. 35 Type C lap joint - France

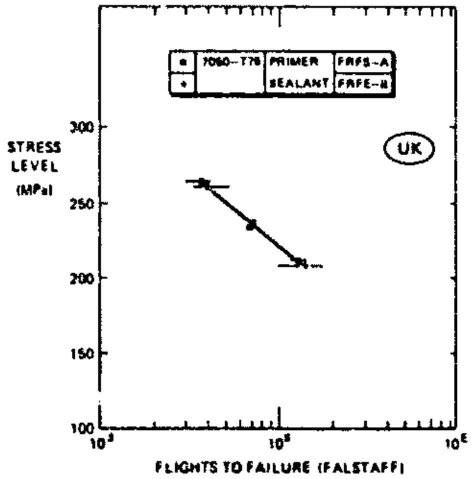


Fig. 36 Q-type joint - United Kingdom

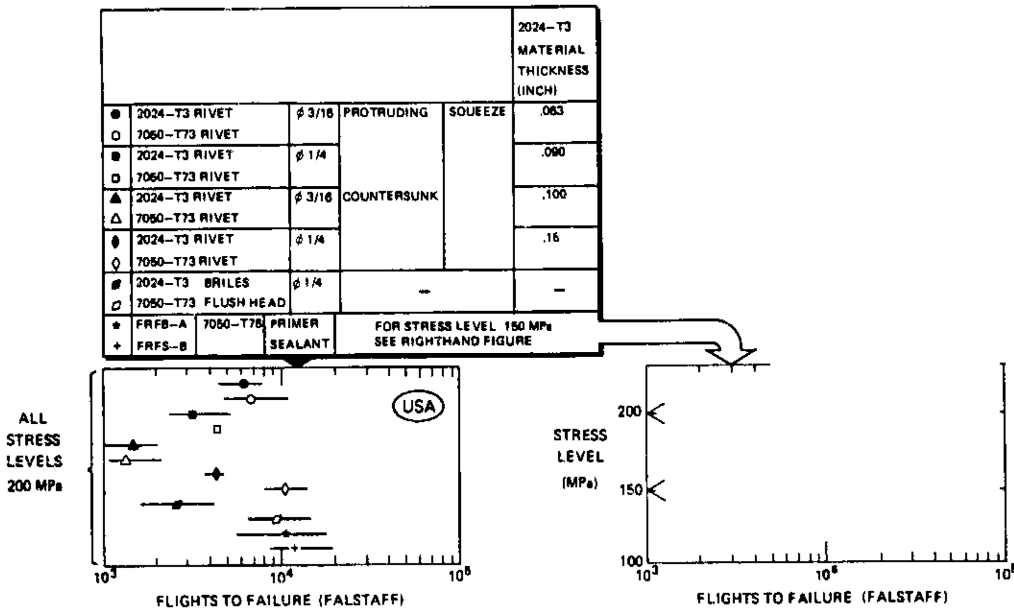


Fig. 37 Type C2 lap joints - USA

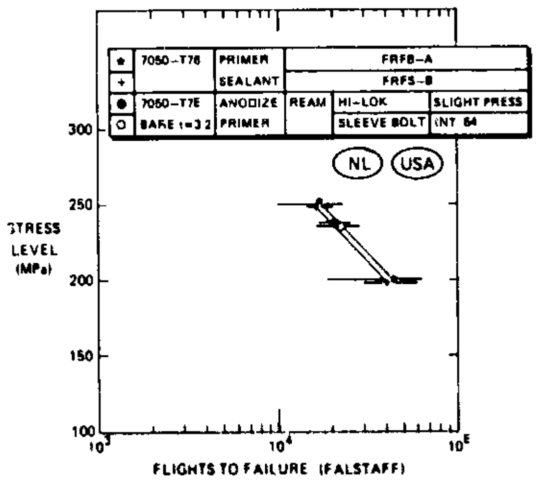


Fig. 38 1½ dogbone joints - the Netherlands and USA

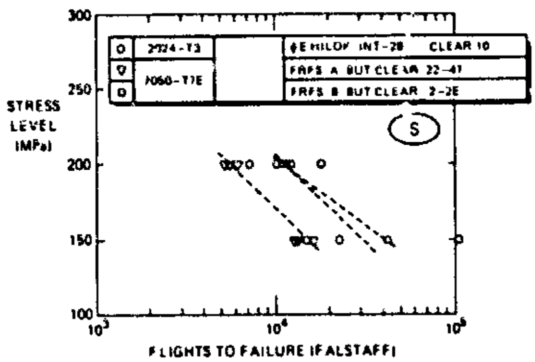


Fig. 39 Single shear X joints - Sweden

FLIGHTS TO FAILURE (F.ALSTAFF)

Fig. 40 Type Cl double shear joint - France

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 41 1½ double shear joint - the Netherlands

Fig. 42 Clamping head used for reverse double dogbone specimen

LOAD TRANSFER AT EACH FASTENER ROW				
	46.7	20.2	33.1	FRFS–A
	44.4	18.3	37.3	FRFS–B

TYPE 'C1'
DOUBLE SHEAR JOINT – FRANCE

LOAD TRANSFER AT EACH FASTENER ROW					
	33.8	21.3	18.3	26.6	FRFS–A'
	41.7	14.8	16.5	27.0	FRFS–B'

TYPE 'D'
DOUBLE SHEAR JOINT – FRANCE

Fig. 43 Load transfer at each fastener row in multiple row double shear joints

PURCHASE COST
(US $/PIECE)
4

Fig. 44 Purchase cost per fastener (US $)

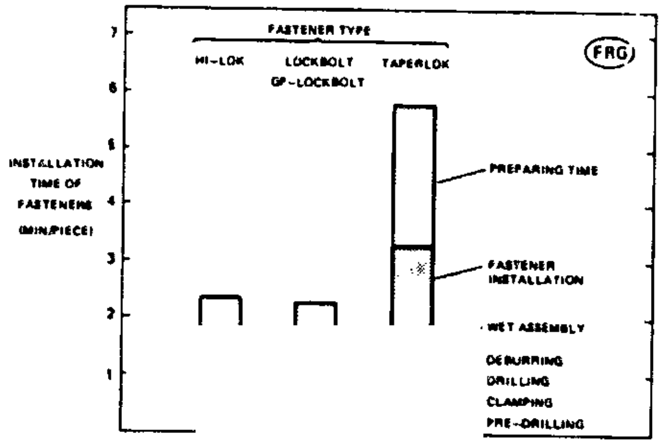


Fig. 45 Installation time of FRG fastener systems

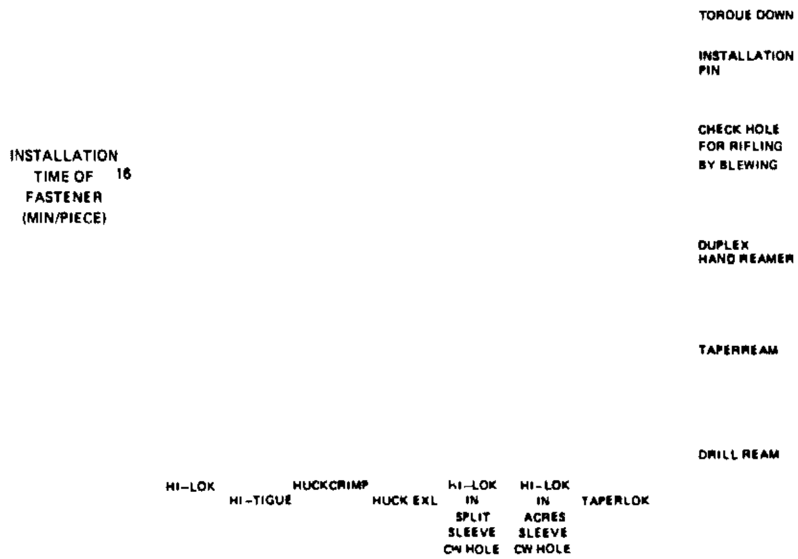


Fig. 46 Installation time of UK fastener systems

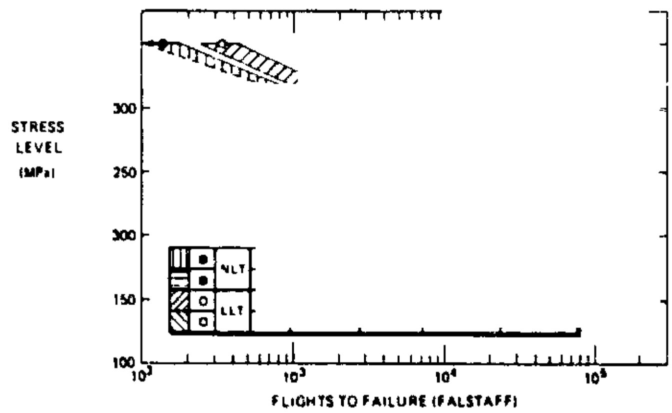


Fig. 47 No load transfer and low load transfer joints - France

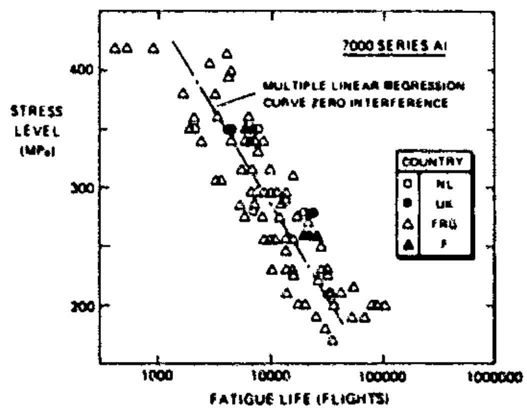


Fig. 48 Analysis of LLT-reverse double dogbone 7000 series specimens

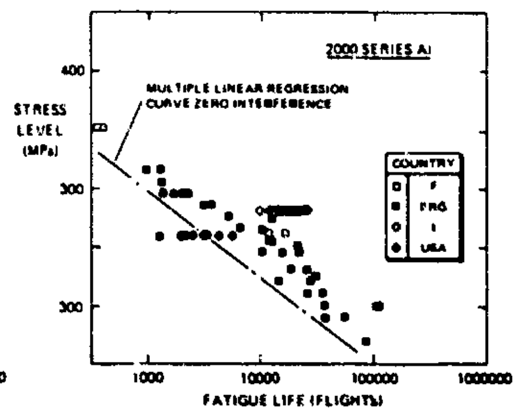


Fig. 49 Analysis of LLT-reverse double dogbone 2000 series specimens

Fig. 50 Fit versus fatigue life, NLT and low load transfer joints, stress level 280 MPa

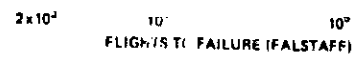


Fig. 51 Fit versus fatigue life, NLT and LLT joints, stress level 280 MPa

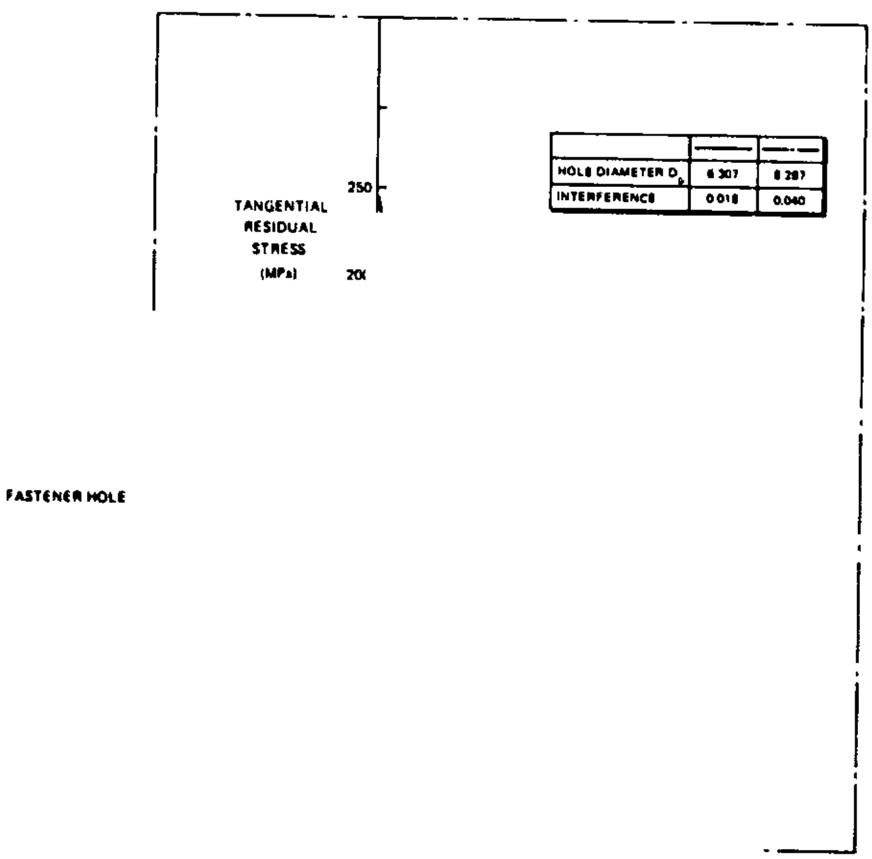


Fig. 52 Tangential stress at fastener hole as a function of the interference, (MBB-VFW)

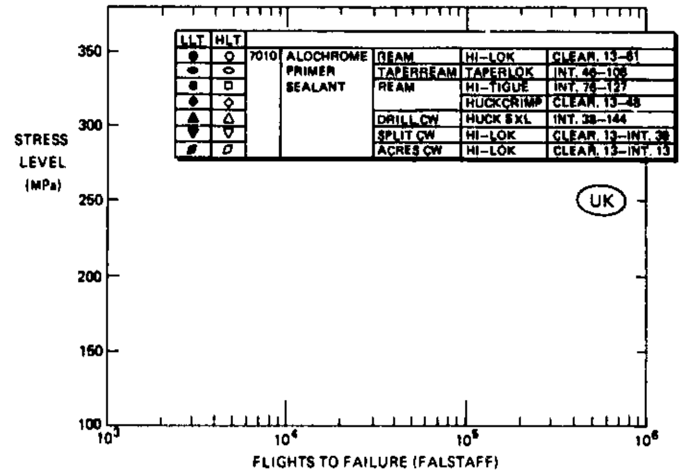


Fig. 53 Log mean fatigue lives of low load transfer and double shear specimens - UK

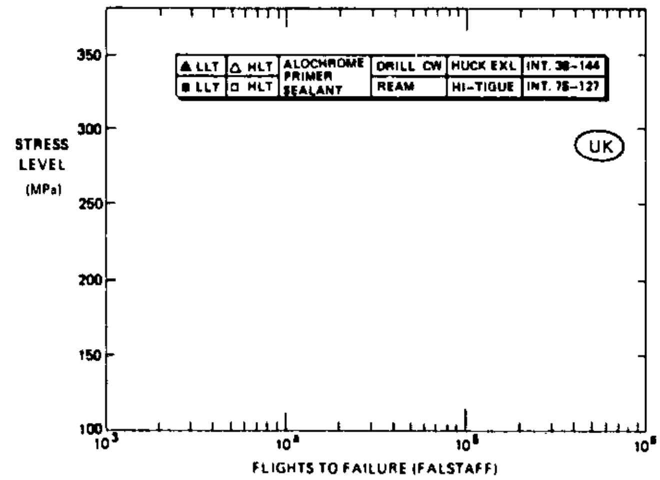


Fig. 54 Fatigue lives of low load transfer and double shear joints - UK

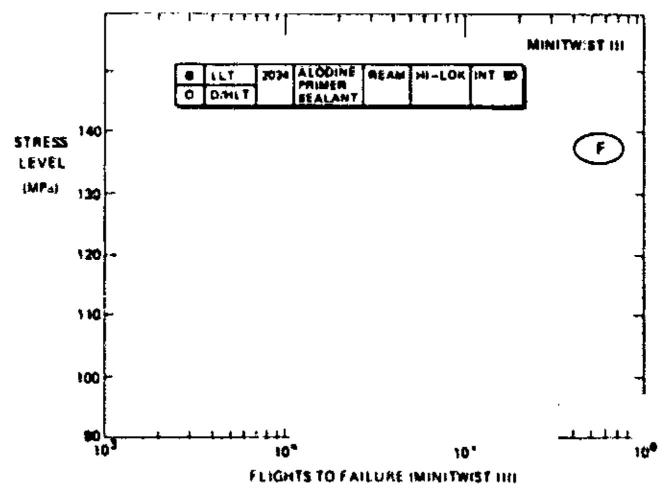


Fig. 55 Fatigue lives of low load transfer and double shear joints - France

FLIGHTS TO FAILURE (MINITWIST III)

FLIGHTS TO FAILURE (MINITWIST III)

Fig. 56 Fatigue lives of low load transfer and double shear (type D) specimen - France

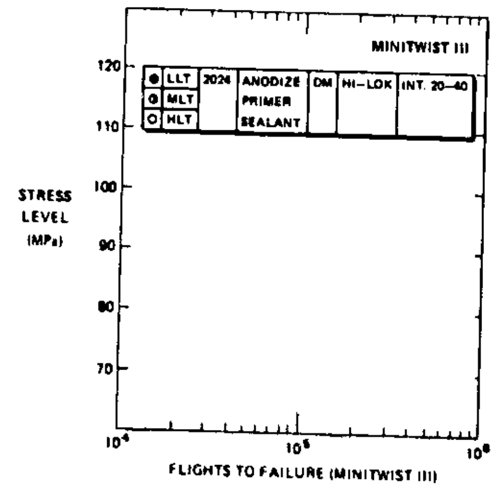


Fig. 57 Low load transfer, medium and high load transfer double shear joints - the Netherlands

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 58 Single shear and double shear core programme specimens

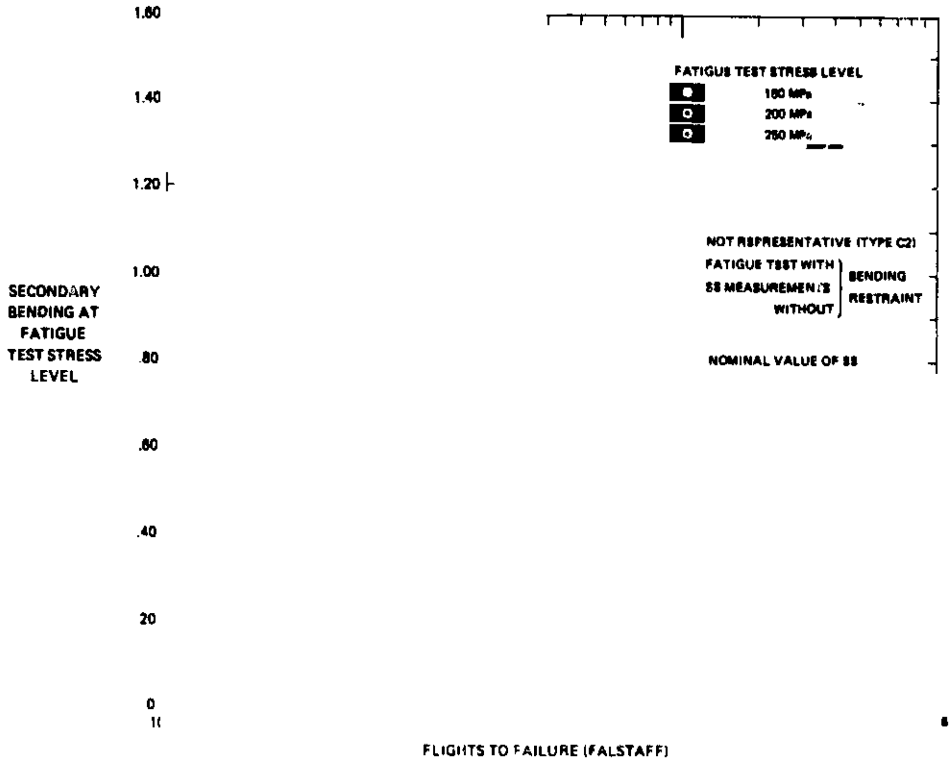


Fig. 59 Fatigue life versus secondary bending for single shear core programme specimens having FRFS-A or FRFS-B

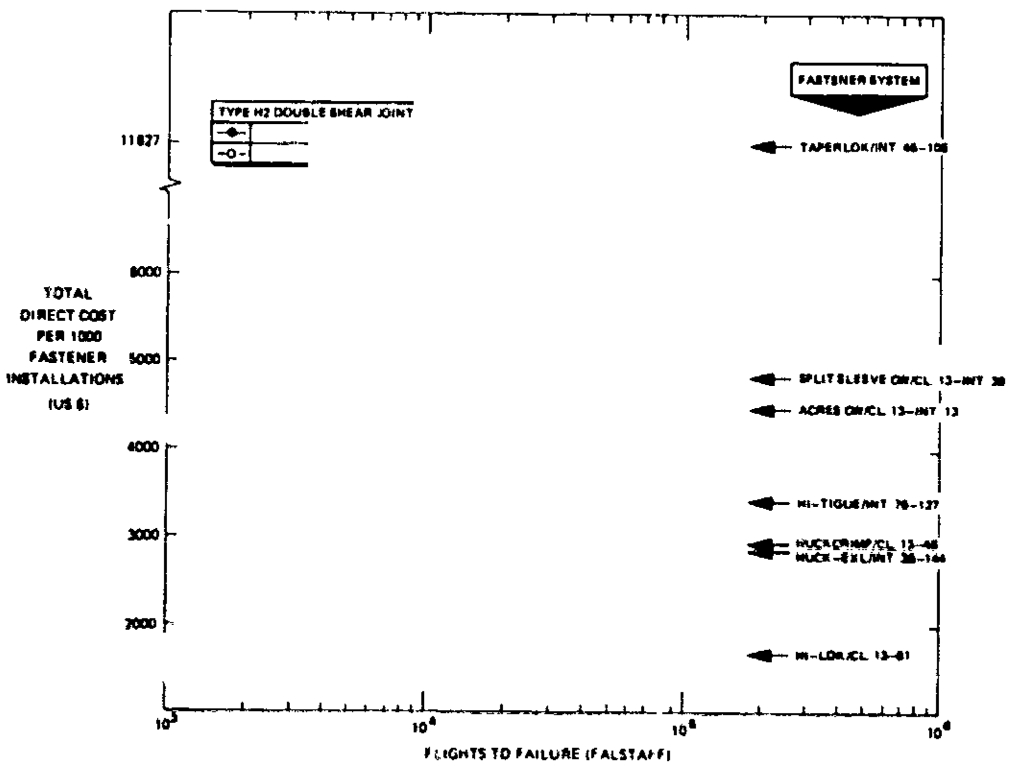


Fig. 60 Log mean fatigue life versus total direct cost per 1000 fastener installations

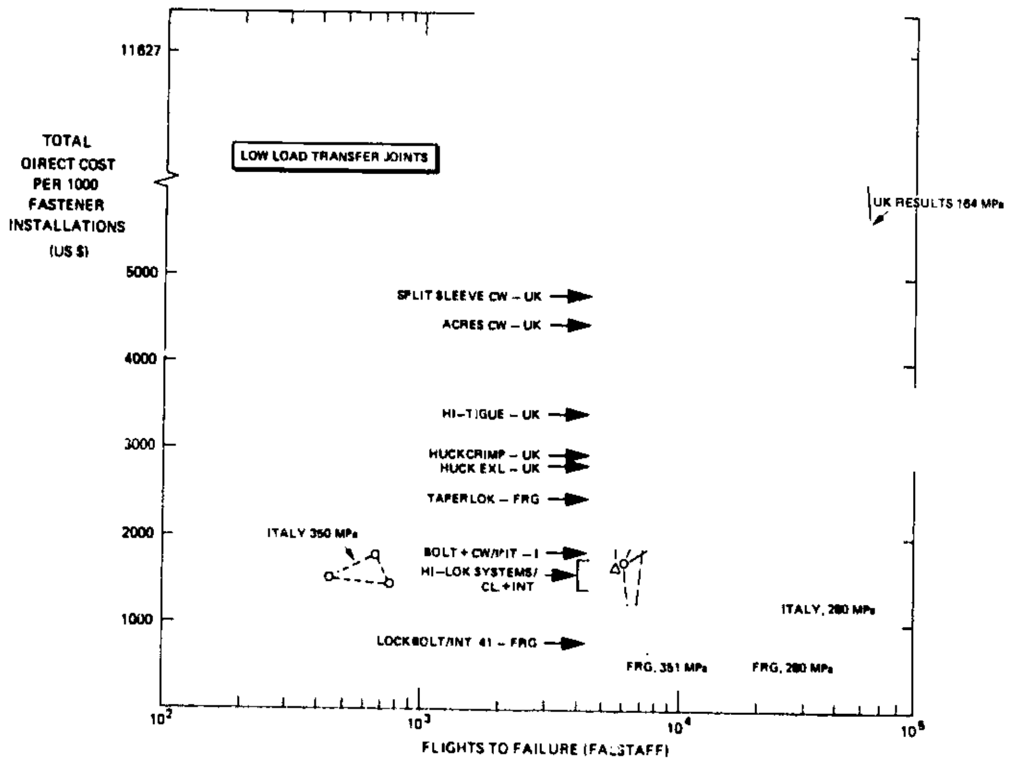


Fig. 61 Log mean fatigue life versus total direct cost per 1000 fastener installations

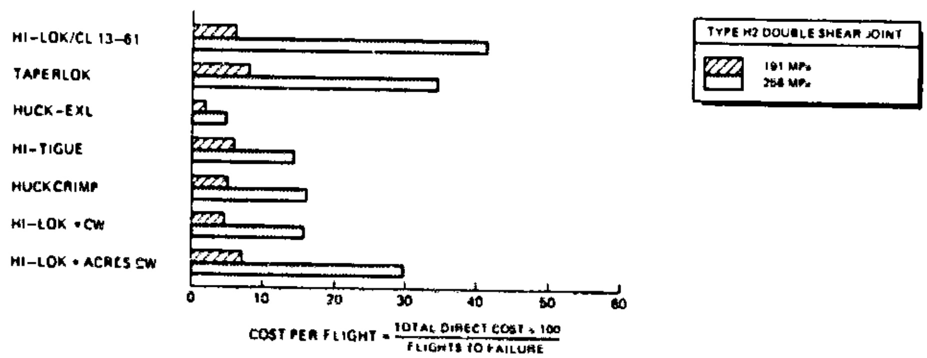


Fig. 62 Comparison of cost per 1000 fastener installations relative the number of flights to failure

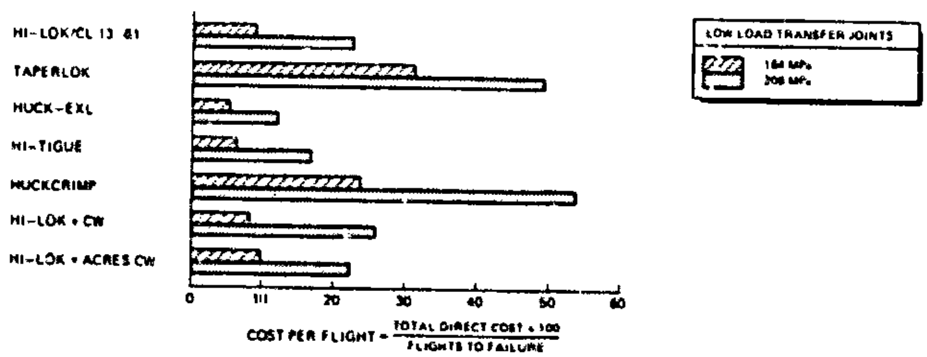


Fig. 63 Comparison of cost per 1000 fastener installations related to the number of number of flights to failure

OBJECTIVES

- DETERMINATION OF FATIGUE LIVES FOR A RANGE OF FATIGUE RATED FASTENER SYSTEMS AND MATERIAL IN COMBINATION WITH HOLE PREPARATION TECHNIQUES
- ESTABLISHMENT OF COST FIGURES IN RELATION TO FATIGUE PERFORMANCE
- IDENTIFICATION OF THE PRIME PARAMETERS INVOLVED IN FASTENER SYSTEM SELECTION
- DEVELOPMENT OF A REFERENCE DATUM FOR THE COMPARISON OF TEST RESULTS PRODUCED IN DIFFERENT COUNTRIES USING DIFFERENT SPECIMEN GEOMETRIES
- DEVELOPMENT OF EXPERIMENTAL METHODS FOR FASTENER SYSTEM FATIGUE RATING

Fig. 1-1 AGARD SMP working group on fatigue rated fastener systems

- EACH PARTICIPANT IDENTIFIED HIS OWN PROGRAMME (ACTIVE OR DESIRED)
- A COMPOSITE TEST MATRIX HAS BEEN CONSTRUCTED FOR DIFFERENT TYPES OF JOINTS.
  - NO LOAD TRANSFER SPECIMENS
  - LOW LOAD TRANSFER SPECIMENS (REVERSE DOUBLE DOGBONE)
  - DOUBLE SHEAR SPECIMENS
  - SINGLE SHEAR SPECIMENS (SECONDARY BENDING)

  MAIN VARIABLES

  - ALUMINIUM ALLOYS
  - FAYING SURFACE TREATMENT
  - MATERIAL THICKNESS
  - FASTENER SYSTEMS, IN COMBINATION WITH FIT
  - HOLE PREPARATION TECHNIQUES
  - FALSTAFF / MINITWIST
  - LOAD LEVELS
- FATIGUE RATED FASTENER SYSTEMS PROGRAMME
  - ADJUSTMENT OF PROGRAMMES TO ELIMINATE UNNECESSARY DUPLICATION AND TO OBTAIN BEST OVERALL PROBLEM COVERAGE
  - DEFINITION OF CORE PROGRAMMES TO CORRELATE TEST RESULTS
  - A LACK OF A SINGLE SHEAR STANDARD SPECIMEN. A RANGE OF HLT JOINT DESIGN WILL BE EVALUATED AND COMPARED
  - FATIGUE LIVES WILL BE EVALUATED IN TERMS OF
    - INSTALLATION COSTS OF THE FASTENER SYSTEM
    - FASTENER SYSTEM AND HOLE PREPARATION TECHNIQUE USED
    - LOCATION OF THE FATIGUE CRACK INITIATION SITES

Fig. 1-2 Methods and means of accomplishment

- **NO LOAD TRANSFER JOINTS**
  - TEST PROGRAMMES: PER THE PARTICIPANTS STANDARDS
  - CORE PROGRAMME, WHICH WILL SERVE AS A REFERENCE DATUM FOR THE COMPARISON OF TEST RESULTS PRODUCED IN FRANCE AND SWEDEN

– PARTICIPANTS	: FRANCE AND SWEDEN
– MATERIAL	: 2024–T3, BARE (t = 4 mm)
– INTERFAY SURFACE TREATMENT	: –
– FASTENER SYSTEM	: TI BOLTS, HEX. AND CSK, ϕ6 mm DRY INSTALLED
– FIT	PER THE PARTICIPANTS STANDARD
– HOLE QUALITY	PER THE PARTICIPANTS STANDARD
– LOAD LEVEL	200 MPa AND 351.5 MPa, GROSS AREA STRESS (FALSTAFF)

  - MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)

- **LOW LOAD TRANSFER JOINTS**
  - TEST PROGRAMMES
    - – ALL PARTICIPANTS, EXCEPT FOR THE UK, USE THE STANDARD REVERSE DOUBLE DOGBONE SPECIMEN (AS USED IN THE CRITICALLY LOADED HOLE TECHNOLOGY PROGRAMME)
    - – FREE LOAD LEVELS 280 MPa AND 351.5 MPa, GROSS AREA STRESS (FALSTAFF)
  - CORE PROGRAMME TO CORRELATE UK TEST RESULTS WITH RESULTS OF THE OTHER PARTICIPANTS

– PARTICIPANT	UK
– MATERIAL	7010–T7651 (t = 5 mm)
– INTERFAY SURFACE TREATMENT	PR 1422
– FASTENER SYSTEM	HI–LOK, ϕ6.35, CSK
– FIT	CLEARANCE, PER UK STANDARD
– HOLE QUALITY	a REAMED, PER UK STANDARD
	b COLD WORKED, REAMED, PER UK STANDARD
– LOAD LEVELS	280 MPa AND 350 MPa, NET SECTION STRESS (FALSTAFF)

  - MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)
  - FRACTOGRAPHIC INVESTIGATION TO ESTABLISH STATISTICAL INFORMATION OF THE CRACK INITIATION SITES

- **DOUBLE SHEAR JOINTS**
  - TEST PROGRAMMES
    - THREE DESIGNS (100%, 50% AND 25% LOAD TRANSFER) WILL BE INVESTIGATED BY THREE PARTICIPANTS
    - FREE LOAD LEVELS 200 MPa AND 250 MPa (SEE TABLE 1.1) GROSS AREA STRESS (FALSTAFF)
  - CORE PROGRAMME TO CORRELATE TEST RESULTS OF DIFFERENT COUNTRIES

– PARTICIPANTS	SWEDEN, UK, THE NETHERLANDS
– MATERIAL	7050–T76 (t = 5 mm)
– INTERFAY SURFACE TREATMENT	EPOXY PRIMER AND INTERFAY SEALANT PR–1431–G
– FASTENER SYSTEMS	a HI–LOK CLEARANCE, REAMED HOLE
	b HI–LOK INTERFERENCE, COLD WORKED HOLE, REAMED HOLE
	c OPTIONAL HI LOK INTERFERENCE, REAMED HOLE
– LOAD LEVELS	200 MPa AND 250 MPa (SEE TABLE 1.1) GROSS AREA STRESS (FALSTAFF)

  - MEASUREMENT OF LOAD TRANSFER OF TEST PROGRAMME – AND CORE PROGRAMME SPECIMENS USING STANDARD PROCEDURES. MEASUREMENTS ON EACH COMBINATION OF SPECIMEN DESIGN AND FASTENER SYSTEM
  - MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)
  - FRACTOGRAPHIC INVESTIGATION TO ESTABLISH STATISTICAL INFORMATION OF THE CRACK INITIATION SITES

Fig. 1-1 Fatigue rated fastener programme, Summary

to be continued

- **SINGLE SHEAR JOINTS**
  - TEST PROGRAMMES: A RANGE OF HIGH LOAD TRANSFER SINGLE SHEAR JOINTS WILL BE TESTED
    - FRFS LOAD LEVELS : 150, 200 AND 250 MPa (SEE TABLE 1.2) GROSS AREA STRESS (FALSTAFF)
  - CORE PROGRAMME TO EVALUATE AND COMPARE DIFFERENT HIGH LOAD TRANSFER SINGLE SHEAR JOINTS. TESTS ON SINGLE SHEAR JOINTS AND THEIR DOUBLE SHEAR EQUIVALENT DESIGNS. THE DOUBLE SHEAR EQUIVALENT DESIGN IS A SIMPLE DERIVATIVE OF THE SINGLE SHEAR SPECIMEN:

THE ASYMMETRICAL SIDEPLATE IS REPLACED BY TWO SYMMETRICAL SIDE PLATES OF THE HALF THICKNESS. THE DOUBLE SHEAR SPECIMEN HAS NO SECONDARY BENDING.

– PARTICIPANTS	USA, FRANCE, SWEDEN, THE NETHERLANDS, UK
– MATERIAL	7050–T76 (t = 6 mm) (IF NECESSARY MATERIAL SHOULD BE MILLED DOWN TO 2.5 mm)
– INTERFAY SURFACE TREATMENT	EPOXY PRIMER AND INTERFAY SEALANT PR–1431–G
– FASTENER SYSTEM	a. HI–LOK, CLEARANCE, REAMED HOLE b. HI–LOK, INTERFERENCE, COLD WORKED HOLE, REAMED c. OPTIONAL: HI–LOK, INTERFERENCE, REAMED HOLE
– LOAD LEVELS	150, 200 AND 250 MPa (SEE TABLE A.2) GROSS AREA STRESS (FALSTAFF)

  - MEASUREMENT OF LOAD TRANSFER AND SECONDARY BENDING OF TEST PROGRAMME– AND CORE PROGRAMME SPECIMENS USING STANDARD PROCEDURES. MEASUREMENTS ON EACH COMBINATION OF SPECIMEN DESIGN AND FASTENER SYSTEM
  - MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)
  - FRACTOGRAPHIC INVESTIGATION TO ESTABLISH STATISTICAL INFORMATION OF THE CRACK INITIATION SITES

Fig. 1-3 Concluded

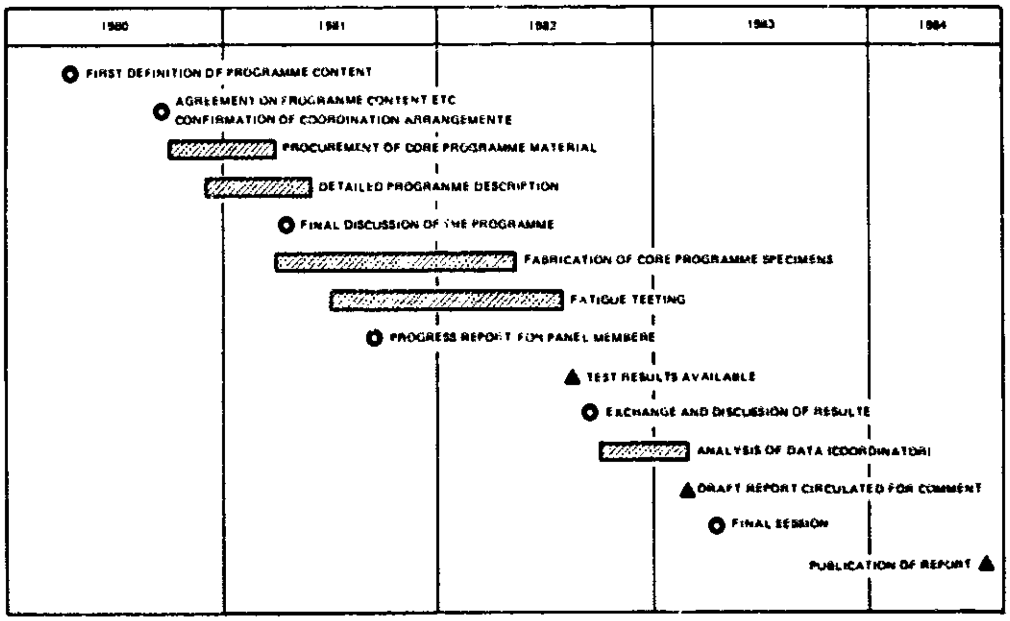


Fig. 1-4 Schedule and milestones for the FRFS programme

TABLE 1-1
Number of specimens for different load levels of the double shear joints core programme

LOAD LEVEL (MPa)	FASTENER SYSTEM		
	HI-LOK, CLEARANCE, REAMED HOLE	HI-LOK, INTERFERENCE, REAMED HOLE	HI-LOK, INTERFERENCE, COLD WORKED AND REAMED HOLE
	NUMBER OF SPECIMENS		
200	3	(3)	3
250	3	(3)	3
280	(3)	(3)	(3)

( ) OPTIONAL

TABLE 1-2
Number of specimens for different load levels of the single shear joints / double shear equivalent core programme

SPECIMEN DESIGN	LOAD LEVEL (MPa)	FASTENER SYSTEM		
		HI-LOK, CLEARANCE, REAMED HOLE	HI-LOK, INTERFERENCE, REAMED HOLE	HI-LOK, INTERFERENCE, COLD WORKED AND REAMED HOLE
		NUMBER OF SPECIMENS		
SINGLE SHEAR JOINTS	150	3	(3)	3
	200	3	(3)	3
	250	(3)	(3)	(3)
DOUBLE SHEAR EQUIVALENT	150	3	(3)	3
	200	3	(3)	3
	250	(3)	(3)	(3)
1 1/2 DOGBONE TYPE JOINTS	150	(3)	(3)	(3)
	200	3	(3)	3
	250	3	(3)	3
DOUBLE SHEAR EQUIVALENT	150	(3)	(3)	(3)
	200	3	(3)	3
	250	3	(3)	3

( ) OPTIONAL

ANNEX 2

ORIGINALLY PUBLISHED AS: APPENDIX A/FRFS/NOV. 1981

FASTENER SYSTEMS

Three fastener systems are selected for application in two core programmes of the Fatigue Rated Fastener Systems programme (see reference 1).
Basically the fastener systems are as follows:

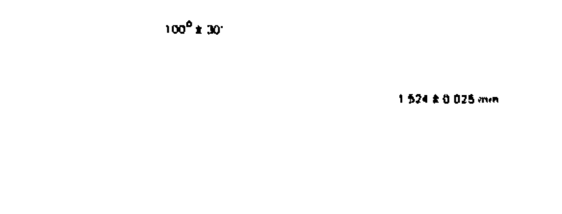
fastener system	hole quality	fastener	fit + clearance - interference (mm)
FRFS-A	reamed	Hi-Lok, CSK, Ø 6.35 mm	+ .020 ± .010
FRFS-B	cold-worked (3 %) and reamed		- .025 ± .010
FRFS-C -OPTIONAL-	reamed		- .090 ± .010

The fastener type selected, hole production procedures, interfay surface treatment and installation procedures are described.

Fasteners
All fasteners to be used are cadmium plate steel Hi-lok HL-19-8-7 together with HL-70-8 collars.
The coding HL-19-8-7 refers to:
- HL-19: pin part number
  - 8: 8/32 inch or 6.35 mm nominal diameter pin
  - 7: 7/16 inch or 11.11 mm maximum grip length.

The collars are made of 2024-T6 aluminium alloy;
the coding - 8 refers to nominal thread size of 8/32 inch or 6.35 mm. The nominal diameter of the pin is 6.35 mm; the specified minimum and maximum diameter are 6.312 mm and 6.337 mm respectively. However, practice shows that the pin diameter is between 6.325 and 6.337 mm.

Fastener holes
Table 2-1 gives the hole preparation for each fastener system. Nominal tool diameters should be selected very carefully by each participant to arrive at the required fit.
The cylindrical parts of all fastener holes must be reamed as a last working procedure.
Countersinking is done after reaming of the cylindrical parts of the fastener holes.
Dimensions of the countersink are given in the following figure:



Dimensions of the countersink

After countersinking all hole edges at interfaying and break out surfaces, except the countersink, are lightly deburred.
As indicated earlier the fastener system B is an interference fit Hi-lok in a cold-worked, reamed hole (see table 2-1).
The holes must be cold-worked using the Split Sleeve Cold Expansion Process (CX) of Fatigue Technology Inc., USA; detailed information about the hole production is given in the following (see also reference 2).
The starting holes shall be reamed to dimensions as given in table 2-1; these dimensions correspond with those of reference 2. If a cutting fluid leaves an excessive lubricant residue in the hole, the residue must be removed before split sleeve cold expansion.
The major and minor diameter of the mandrel are given in figure 2-1. The mandrel major diameter is allowed to shrink or wear a maximum of .015 mm (.0006 inches) from the nominal diameter before replacement.
Use of a reamer with a non-cutting pilot is required as a quality control measure to ensure that all holes are cold expanded prior to post sizing. The pilot diameter will not fit into a starting hole, but will fit into a cold expanded hole.
The cold expanded hole has an axial ridge which corresponds with the position of the split in the sleeve.
Post sizing is required to clean up the hole in order to provide the desired fastener fit.
The maximum metal removal is limited to 10 % of the nominal hole diameter or 1.575 mm (0.062 inches), whichever is less.
The FTI process specification allows that the finished hole contains a region near the entry, exit or interface which does not totally clean up during the post sizing operation. The hole will be acceptable providing the region does not extend axially by more than .508 mm (.020 inches) or 10 % of the detail thickness, whichever is less.
Machining of countersinks shall be performed after post size reaming. All hole edges at interfaying and break out surfaces, except the countersink, are lightly deburred.

Faying surface treatment and assembly of specimens

Common to all participants of the Double Shear and Single Shear Core Programmes is the schema of faying surface treatment and wet installation of the fasteners. Following machining, hole production and measurement of all holes (see reference 3) specimens will receive a faying surface treatment as follows:

- cleaning (degreasing) with suitable solvent;
- application of epoxy primer, except in countersunk holes, to a dry film thickness of .05 - .13 mm;
- cure primer;
- upon assembly the faying surfaces of the joint specimens will be coated with Products Research and Chemical Corporation (PRC) PR-1431G or equivalent. The sealant is applied using a standard short nap paint roller (see PRC Interim Technical Data Sheet for the PR-1431-G corrosion inhibitive sealant);
- no topcoat is to be applied to the specimens.

References

1. Van der Linden, H.H., AGARD SMP Working Group on FRFS, Revision C, July 1981.
2. CX Process Specification: Cold Expansion of Fastener and other Holes using the Split Sleeve System, FTI 8101, Fatigue Technology Inc. Draft, May 1981.
3. Measurement of fit and surface roughness, Appendix B / FRFS, August 1981. Also as Annex 3 of this report.

TABLE 2-1
Fastener systems

FASTENER SYSTEM CODE	FRFS-A	FRFS-B	FRFS-C optional
FASTENER	Hi-LOK HL-19-8-7. nom. dia 6.35 min. dia. 6.312, max. dia. 6.337 practice: dia. 6.325 - 6.337		
PREDRILL	X	X	X
DRILL	X	X	X
REAM	X	TO: 5.71 - 5.79 mm	X
COLD WORK		3 % split sleeve process (CX) of FTI	
REAM		X	
COUNTERSINKING. DEBURRING OF ALL HOLE EDGES, except the countersink MEASUREMENT OF FIT INTERFAY SURFACE TREATMENT - cleaning - epoxy primer - sealant PR-1431-G WET INSTALLATION OF FASTENERS (PR-1431-G)			
FIT + clearence -interference	±.010 +.020	±.010 -.025	±.010 -.090

(dimensions in mm)

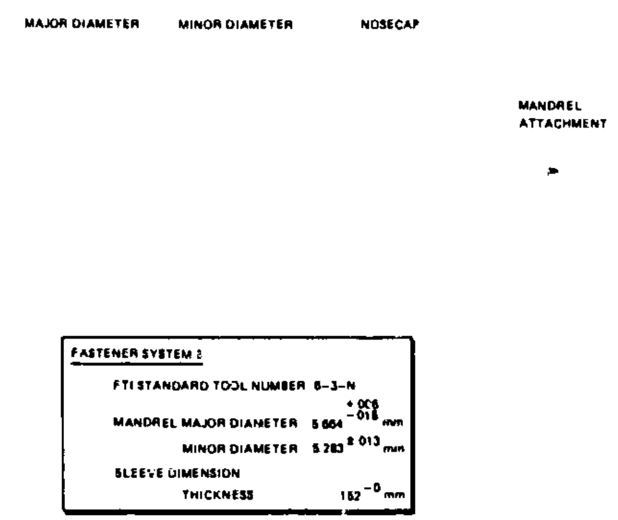


Fig. 2-1 Split sleeve cold expansion mandrel

ANNEX 3

ORIGINALLY PUBLISHED AS: APPENDIX E / FRFS - AUGUST 1981

MEASUREMENT OF FIT AND SURFACE ROUGHNESS

In order to establish the fit of each fastener/hole combination the hole and fastener dimensions should be characterized. Measurements should be noted on a special form (table 3-1), developed by VFW-Bremen.
The procedure is as follows (see table 3-1)

* Each Specimen:
  - specimen identification;
  - identification of the fastener holes.

* Each fastener hole
  a measurement of two diameter (perpendicular) on the top side of the specimen, calculation of the average value;
  b measurement of two diameters (perpendicular) on the bottom side of the specimen, calculation of the average value;
  c average figures found under a and b;
  d measure the fastener diameter (twice);
  e calculate the average fastener diameter;
  f establish the fit.

An example is given in table 3-2.
The hole surface roughness should be characterized using in house equipment.

TABLE 3-1
Measurement of fit and surface roughness

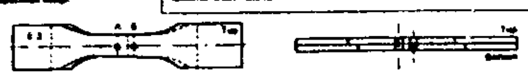
Spec. No	Hole No	Hole Dia. ϕ top: Measurement 1	Hole Dia. ϕ top: Measurement 2	Hole Dia. ϕ top: Average	Hole Dia. ϕ bottom: Measurement 1	Hole Dia. ϕ bottom: Measurement 2	Hole Dia. ϕ bottom: Average	ϕ Average	Fastener Dia. ϕ: Measurement 1	Fastener Dia. ϕ: Measurement 2	Fastener Dia. ϕ: Average	Fit: Interf.	Fit: Clearance	No of Fast.	Roughness	Notes

TABLE 3-2
Measurement of fit and surface roughness. An example

Spec. No	Hole No	Hole Dia. ϕ top: Measurement 1	Hole Dia. ϕ top: Measurement 2	Hole Dia. ϕ top: Average	Hole Dia. ϕ bottom: Measurement 1	Hole Dia. ϕ bottom: Measurement 2	Hole Dia. ϕ bottom: Average	ϕ Average	Fastener Dia. ϕ: Measurement 1	Fastener Dia. ϕ: Measurement 2	Fastener Dia. ϕ: Average	Fit: Interf.	Fit: Clearance	No of Fast.	Roughness	Notes
6 3	A	6.316	6.312	6.311	6.320	6.314	6.317	6.314	6.334	6.333	6.333	0.019				
	B	6.308	6.312	6.310	6.316	6.313	6.314	6.312	6.331	6.333	6.332	0.020				

Specimen design

Specimen sheet material



Fastener [illegible] HL 10VPB-6
Type ϕ mm
All dimensions in mm

ANNEX 4

DETERMINATION OF SECONDARY BENDING AND LOAD TRANSFER

SUMMARY

For use in the AGARD SMP Fatigue Rated Fastener Systems Programme a procedure for the determination of secondary bending and load transfer is described.

1. INTRODUCTION

At the fall 1980 FRFS Working Group meeting agreement was reached on the programme content (references 1, 2). In the "Single Shear Joints Core Programme" the amount of secondary bending and load transfer is to be measured.
The Working Group adopted a procedure for the measurement of secondary bending; this procedure was proposed by Dr. D. Schütz (LBF) and is described fully in this annex.
This memorandum also describes a procedure for the determination of load transfer; this procedure will also be used in the "Double Shear Joints Core Programme".
It is strongly recommended by the FRFS Working Group members to use the procedures described herein.

2. DETERMINATION OF SECONDARY BENDING

By definition secondary bending is caused by an excentricity. The procedure described is based on the measurement of strains during loading and unloading.
The position of the strain gauges, the definition of secondary bending, the load application and a typical example are described in the following.

2.1 Position of the strain gauges

The secondary bending is interest at the critical cross-section, i.e. the cross-section where the fatigue crack occurs. Usually a crack will start at a hole or at the faying surface close to a hole.
The location of crack initiation is not accessible in most cases; so a neighbouring position must be chosen for the measurement.

The following convention has been adopted (reference 3) for choosing the position of the strain gauges.

a) In the case of joints with several fasteners in a row the position of the strain gauges is given in figure 4-1.

b) In the case of joints with one fastener in a row the position of the strain gauges is given in figure 4-2.

At each position, as defined under a) and b), two strain gauges should be bonded, i.e. one at each side of the plate (figures 4-1 and 4-2).
In order to accommodate the interference gauge(s) and wires shallow recesses should be manufactured in the opposite plate (references 3, 4, 5).

Further it is recommended to use strain gauges with a grid length and width of 3 mm and 1.5 mm respectively.

2.2 Definition of secondary bending

The definition of secondary bending is given in figure 4-3.
The bending and axial component of the strain are derived using the strains measured at the opposite sides of the plate.
The secondary bending ratio (references 4, 6) is given by the ratio of the bending strain and the axial strain at the position under consideration.

2.3 Load application

The measurement of secondary bending is carried out under static loading. The load steps are given in table 4-1. Load is given relative to the maximum load in the FALSTAFF sequence. 1)

Table 1 also may be used for reporting of the measurements made.

During the first load cycle a hysteresis loop, load vs strain, may be obtained indicating that residual deformation is involved arising from the fastener deformation and yielding of highly stressed regions. Therefore the measurement should be repeated after a number of load cycles, in order to obtain a stabilized load-strain curve (see also 2, 4).

1) Note: The loads applied in the measurement should cover the loads that will be applied in the fatigue tests.

2.4 A typical example

A typical joint, namely the single shear lap joint (figure 4-4) was investigated in reference 3.
The loads applied were established in such a way that all fatigue tests carried out remained within the load range as used in the measurement of secondary bending.
The load sequence applied was: zero-maximum load-zero-minimum load-zero.

Results of the first load cycle are given in figure 4-5.
Also stabilised load-elongation curves were obtained: an approximate linear relationship was found (figure 4-5).

3. DETERMINATION OF LOAD TRANSFER

In joints load is transmitted from one plate to another at each fastener row. The determination of load transfer is based on strain measurements during loading and unloading.
The position of the strain gauges, the definition of load transfer and load application are described in the following.

3.1 Position of the strain gauges

The position of the strain gauges is given in figure 4-6.
At site 'a' the total (axial) load, carried through the joint, is measured.
At site 'c' the bypass load (figure 4-7) is measured.
The variation in load transfer over cross-section "A" is established using a number of strain gauges; the position of the strain gauges is given in figure 4-6. In order to exclude the effect of secondary bending loads the strain gauges should be bonded on opposite sides of the plate. Shallow recesses should be manufactured in the opposite plate to accommodate the interference gauge(s) and wires; the dimensions of the shallow recess are given in figure 4-1. The dimensions of the strain gauges are given in section 2.1.

3.2 Definition of load transfer

Load transfer is defined as the load which is transferred from one plate to another.
That part of the load which is not transferred is called the bypassing load. Load transfer and bypassing load are given schematically in figure 4-7.
Load transfer -in most cases- is expressed as the percentage of the total load each fastener row transmits (reference 4); therefore the percentage of load transfer is given by:

$$\frac{\text{axial load site 'a' - axial load site 'c'}}{\text{axial load site 'a'}} \times 100\ \%$$

3.3 Load application

The procedure is identical to the one used in the determination of secondary bending; therefore see section 2.3 of this memorandum.

4. CONCLUSIONS

Procedures for the determination of secondary bending and load transfer, based upon the usage of strain gauges have been described.
The strain gauge measurements are carried out at a number of steps under static loading.
From the measurement the secondary bending ratio and the percentage of load transfer can be derived.

5. REFERENCES

1. Heath, W.G., Fatigue Rated Fasteners. AGARD SMP. Sub-Committee Report, Fall 1980.

2. Van der Linden, H.H., Working Group on Fatigue Rated Fastener Systems, Revision C, July 1981.

3. Schütz, D. and Lowack, H., The Effect of Secondary Bending on the Fatigue Strength of Joints. Laboratorium für Betriebsfestigkeit, Report FB - 113 (1974). RAE Library Translation 1858.

4. Perrett, B., Some Measurements of Load Transfer and Secondary Bending in Fastener - Joint Specimens for the Proposed Evaluation of 'Fatigue Resistant' Fasteners. RAE Tech. Memo Structures 950.

5. Jarfall, J., Review of Some Swedish Works on Aeronautical Fatigue During the Period May 1973 to April 1975. FFA Technical Note No. HE-1684.
Also in: Minutes of the Fourteenth Conference on the International Conference on Aeronautical Fatigue (ICAF), Lausanne, 1975, ICAF-Document No. 800.

6. Schütz, D., Franz, J. and Gerharz, J.J., Der Einfluss der Lastübertragung auf der Schwingfestigkeit von Fügungen mit Schubbeanspruchten Befestigungselementen. Fraunhofer Institut für Betriebsfestigkeit (LBF), Institutsveröffentlichungen, Heft 9, 1980, pp. 141-154.

TABLE 4-1
Values of load transfer and secondary bending ratio

Specimen type	____________
Specimen number	____________
Max. load (MPa)	____________
Min. load (MPa)	____________

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		
16.7		
33.3		
50		
66.7		
83.3		
100		
83.3		
66.7		
50		
33.3		
16.7		
0		
minimum load		
0		

TANGENT TO THE SHAFT
OF THE FASTENERS

SECTION A – A

SHALLOW RECESS
(WIDTH ≤5 mm)

Fig. 4-1 Position of strain gauges in secondary bending measurements in joints with several fasteners in a row

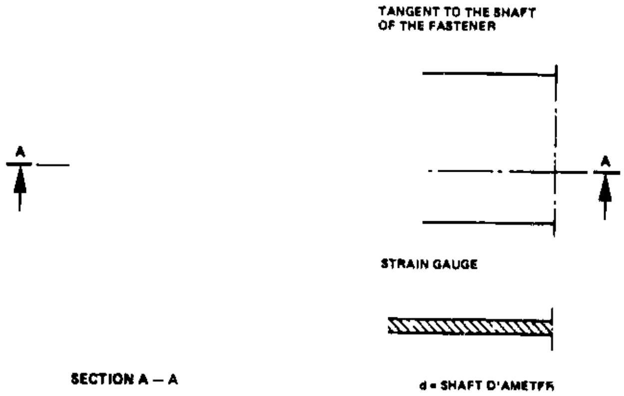


Fig. 4-2 Position of strain gauges in secondary bending measurements with one fastener in a row

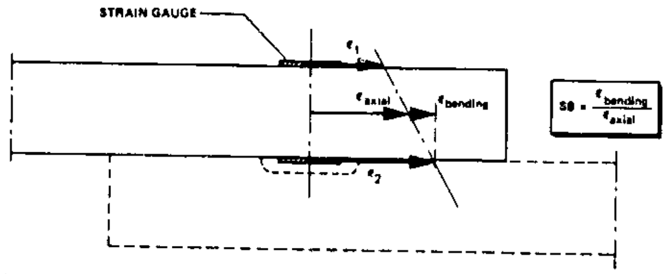


Fig. 4-3 Definition of secondary bending

60x01

SPECIMEN MATERIAL
3.1364.5

FASTENER
HUCKBOLT, STEEL
Ø 3/16

Fig. 4-4 Single shear lap joint used for measurement of secondary bending (Ref. 4.3) - Not the FRFS procedure

ZERO POINT FOR
STABILIZED
MEASUREMENT

Fig. 4-5 Relationship between measured elongation and external load; single shear lap joint (fig. 4.4) (Ref. 4.3)

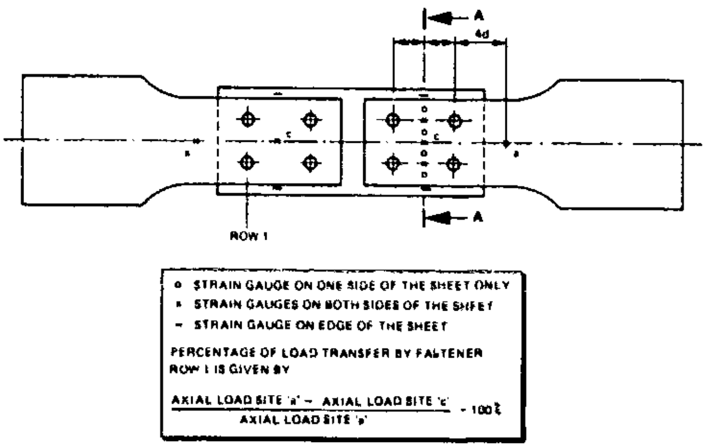


Fig. 4-6 Determination of the percentage of load transfer

ANNEX 5

RESULTS OF THE MEASUREMENTS OF SECONDARY BENDING AND LOAD TRANSFER

This section presents the full details of the measurements of secondary bending and load transfer. Table 5-1 to to 5-18 presents the values of secondary bending and load transfer as reported by the participants.
Figure 5-1 to 5-3 present graphically the secondary bending and load transfer as function of the applied load. Table 13 of the main section of this report summarizes the values of secondary bending and load transfer.

TABLE 5-1
Values of load transfer and secondary bending ratio - France

Specimen type	REVERSE DOUBLE DOGBONE
Specimen number	7-1 2024 "Gamma D" - HI-LOK REAM; INTERFERENCE 80 μm Alodine 1200, primer + PR1422
Max. load (MPa)	250
Min. load (MPa)	-54

% of the maximum load in FALSTAFF	Secondary bending ratio SB1	Secondary bending ratio SB2	% load transferred
0	.409	.249	-
16.7	.359	.231	8.7
33.3	.333	.211	7
50	.314	.193	6.4
66.7	.295	.177	5.8
83.3	.273	.159	5.3
100	.256	.150	4.9
83.3	.277	.161	4.3
66.7	.298	.174	4
50	.322	.192	4
33.3	.342	.215	4.1
16.7	.366	.240	5.9
0	.397	.254	-
minimum load	.370	.234	-10.4
0	.371	.243	-

$$LT = \frac{M_2 - M}{M} \times 100$$

$$M = \frac{M_1 + M_2}{2}$$

M = axial strain (mean) in top sheet

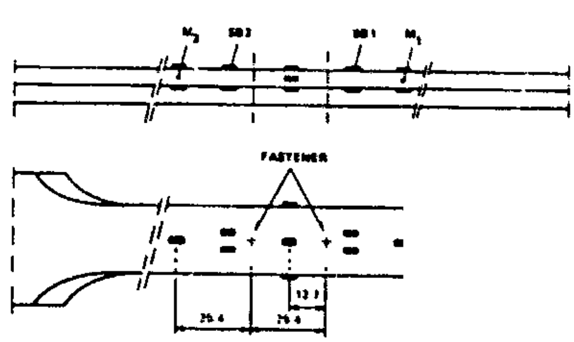


TABLE 5-2
Values of load transfer and secondary bending ratio - France

TABLE 5-3
Values of load transfer and secondary bending ratio - France

Specimen type
Specimen number
Max. load (MPa)
Min. load (MPa)

TABLE 5-4
Values of load transfer and secondary bending ratio - France

Specimen type	TYPE C - FRANCE, HI-LOK. CLEARANCE 10-30 µm, FRFS-A	
Max. load (MPa)	200	
Min. load (MPa)	-53.3	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	-	-
16.7	1.37	48.2
33.3	1.45	55.4
50	1.42	55.4
66.7	1.35	54.8
83.3	1.29	54.3
100	1.23	53.9
83.3	1.23	56.9
66.7	1.26	59.5
50	1.30	62.9
33.3	1.32	68.3
16.7	1.28	84.5
0	-	-
minimum load	-6.39	38.1
0	-	-

TABLE 5-5
Values of load transfer and secondary bending ratio - France

Specimen type	C, HI-LOK, COLD WORK, INTERFERENCE 15-35 µm, FRFS-B	
Max. load (MPa)	200	
Min. load (MPa)	-53.3	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	-	-
16.7	1.62	43.2
33.3	1.68	42.4
50	1.64	41.2
66.7	1.57	41.5
83.3	1.49	41.8
100	1.42	43.1
83.3	1.45	45.5
66.7	1.49	41.7
50	1.53	41.3
33.3	1.57	39.7
16.7	1.58	38
0	-	-
minimum load	-2.95	24.8
0	-	-

NOTE: without sealant

FIGURE SEE TABLE 5-4

TABLE 5-6
Values of load transfer and secondary bending ratio - UK

Specimen type	Q-TYPE, NON COLD-WORKED, HI-LOK	
Specimen number	10	
Max. load (MPa)	350 NET	
Min. load (MPa)	-107 NET	
test run, cycle nr.	AFTER 20.000 CYCLES BETWEEN 0 AND 30 kN	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	0	0
16.7	.245	34.0
33.3	.295	38.5
50	.360	42.5
66.7	.395	45.5
83.3	.430	47.5
100	.440	49.0
83.3	.400	50.0
66.7	.350	48.0
50	.300	52.5
33.3	.260	54.0
16.7	.370	55.0
0	0	0
minimum load	.360	40.0
0	0	0

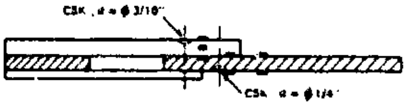


TABLE 5-7
Values of load transfer and secondary bending ratio - UK

Specimen type	Q-TYPE, COLD-WORKED, HI-LOK	
Specimen number	3	
Max. load (MPa)	380 NET	
Min. load (MPa)	-85.6 NET	
test run, cycle nr.	AFTER 20.000 CYCLES BETWEEN 0 AND 30 kN	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	0	0
16.7	.344	33.5
33.3	.442	33.2
50	.522	39.6
66.7	.547	40.9
83.3	.537	42.1
100	.528	43.3
83.3	.512	43.4
66.7	.493	43.3
50	.475	43.8
33.3	.471	44.3
16.7	.48[illegible]	44.5
0	0	0
minimum load	.277	37.0
0	0	0

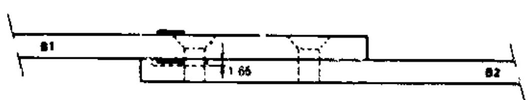
FIGURE SEE TABLE 5-6

TABLE 5-8
Values of load transfer and secondary bending ratio - USA

Specimen type	C2 SINGLE SHEAR
Specimen number	B1/B2
Max. load (MPa)	196.85
Min. load (MPa)	0
test run/cycle nr.	4

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	secondary bending ratio for strain gauges: 1&2	3&4	5&6
0					
16.7	1.32		1.37	1.34	1.24
33.3	1.30		1.37	1.31	1.23
50	1.18		1.23	1.20	1.12
66.7	1.09		1.12	1.10	1.04
83.3	1.07	not	1.08	1.09	1.04
100	1.05	established	1.05	1.06	1.03
83.3	1.04		1.09	1.03	1.00
66.7	1.02		1.03	1.04	1.00
50	1.11		1.12	1.12	1.08
33.3	1.24		1.27	1.25	1.21
16.7	1.43		1.45	1.44	1.40
0					
minimum load	-		see figure below		
0	-see note-				

1) average of 6 gauges



NOTE:
STRAIN GAUGE INSTRUMENTATION NOT ACCORDING TO FRFS PROCEDURES

USA

DIMENSIONS IN mm

TABLE 5-9
Values of load transfer and secondary bending ratio - The Netherlands

Specimen type	1½ DOGBONE - FRFS-A
Specimen number	3A1
Max. load (MPa)	60.5 kN
Min. load (MPa)	-16.2 kN
cycle nr.	5 and 100

% of the maximum load in FALSTAFF	Secondary bending ratio		% load transferred		
	cycle 5	cycle 100	cycle 5	cycle 100	cycle 1000
0	0	0		0	
16.7	.018	.041		25.2	25.9
33.3	.068	.018		23.7	24.7
50	.009	.027		23.8	23.8
66.7	-.048	-.005		24.6	24.6
83.3	-.094	-.055		25.5	25.1
100	-.126	-.095		25.8	25.7
83.3	-.082	-.058		25.5	25.5
66.7	-.041	-.028		24.7	24.3
50	+.019	+.001		24.1	23.1
33.3	.067	+.026		23.5	22.4
16.7	.065	+.026		22.6	20.9
0					
minimum load	-.075	+.054		13.6	12.7
0					

TABLE 5-10
Values of load transfer and secondary bending ratio - The Netherlands

Specimen type	1½ DOGBONE - FRFS-B
Specimen number	3B1
Max. load (MPa)	60.4 kN
Min. load (MPa)	-16.2 kN
cycle nr.	5

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	
	cycle 5	cycle 5	cycle 1000
0	0	0	0
16.7	-.086	20.1	22.6
33.3	.031	21.5	22.1
50	.142	22.1	22.1
66.7	.187	26.2	22.2
83.3	[illegible]	25.5	[illegible]
100	[illegible]	25.1	23.8
83.3	.211	24.5	23.3
66.7	.180	23.5	22.9
50	.140	21.2	23.1
33.3	.060	19.7	23.6
16.7	-.023	15.4	24.9
0	-	-	-
minimum load	-.055	32.6	19.5
0	-	-	-

No data at cycle 1000 available

TABLE 5-11
Values of load transfer and secondary bending ratio - France

Specimen type	C1, HI-LOK, CLEAR, 10-30 μm FRFS-A
Max. load (MPa)	250
Min. load (MPa)	-66.7

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	
		LT1	LT2
0		-	-
16.7		43.9	68.2
33.3		44.6	68.4
50		45.5	67.5
66.7		46.1	67.1
83.3		46.5	67
100		46.7	66.9
83.3		47.1	68.8
66.7		47.1	69.6
50		46.6	70.7
33.3		45.6	72.4
16.7		42.4	76.6
0		-	-
minimum load		46.2	62.8
0		-	-

NOTE: without sealant

$$LT1 = \frac{\varepsilon - \varepsilon_1}{\varepsilon} \times 100$$

$$LT2 = \frac{\varepsilon - \varepsilon_2}{\varepsilon} \times 100$$

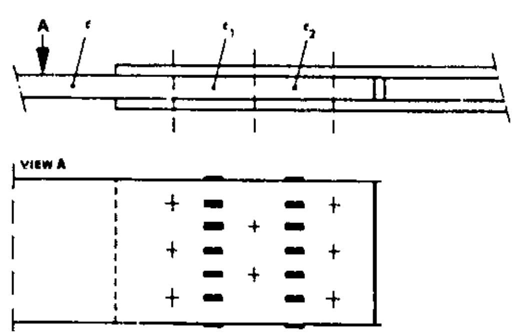


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TABLE 5-12
Values of load transfer and secondary bending ratio - France

Specimen type	Cl, COLD WORK, INT. 15-35 μm FRFS-B
Max. load (MPa)	250
Min. load (MPa)	-66.7

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	
		LT1	LT2
0		-	-
16.7		43	52.1
33.3		41.9	57.5
50		41.7	59.5
66.7		42.8	61.3
83.3		43.7	62
100		44.4	62.7
83.3		44.4	63.5
66.7		44.4	63.7
50		44.2	63
33.3		43.6	62.9
16.7		38.2	58.7
0		-	-
minimum load		44.6	58.2
0		-	-

NOTE: without sealant

FIGURE SEE TABLE 5-11

TABLE 5-13
Values of load transfer and secondary bending ratio - France

Specimen type	D FRFS-A'
Max. load (MPa)	250
Min. load (MPa)	-66.7

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred		
		LT1	LT2	LT3
0		-	-	-
16.7		23.8	47.3	54.9
33.3		28.5	51.7	69.7
50		31.5	53.8	73.2
66.7		32.4	54.5	74.2
83.3		33.5	54.8	74.4
100		33.9	55.2	74.5
83.3		32.9	55.1	75.7
66.7		32.3	54.8	76.2
50		31.6	54.7	76.1
33.3		29.4	54.0	76.7
16.7		22.9	53.4	79.3
0		-	-	-
minimum load		54.0	62.6	88.7
0		-	-	-

NOTE: without sealant

$$LT_i = \frac{\varepsilon - \varepsilon_i}{\varepsilon} \times 100$$

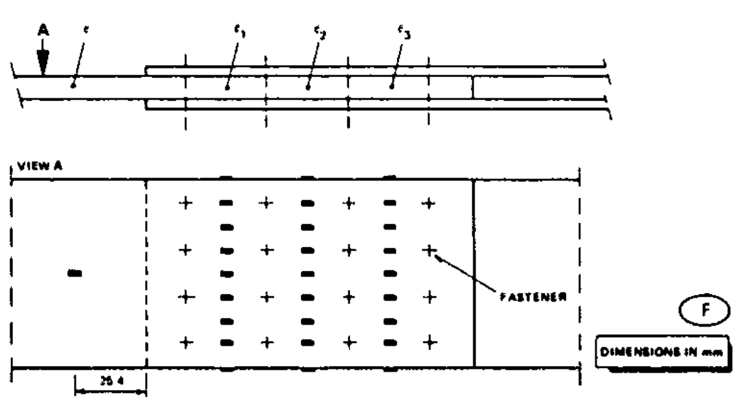


TABLE 5-14
Values of load transfer and secondary bending ratio - France

Specimen type	D, FRFS-B', COLD WORK
Specimen number	HI-LOK, Int. 15-35 µm
Max. load (MPa)	250
Min. load (MPa)	-67

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred		
		LT1	LT2	LT3
		-	-	-
0		46.3	57.6	67.2
16.7		44.1	57.1	69.8
33.3		42.9	57.1	71.0
50		41.8	56.6	71.3
66.7		41.7	56.4	72.2
83.3		41.7	56.5	73.0
100		41.1	56.1	73.2
83.3		40.8	55.7	72.7
66.7		40.4	55.2	72.6
50		40.8	55.5	72.6
33.3		39.2	54.4	72.4
16.7		-	-	-
0		-	-	-
minimum load		-	-	-
0				

NOTE: without sealant

FIGURE SEE TABLE 5-13

TABLE 5-15
Values of load tranafer and secondary
bending ratio - The Netherlands

Specimen type Specimen number Max. load (MPa) Min. load (MPa)	1½ DOGBONE DOUBLE SHEAR 4A11 FRFS-A 250 MPa, 60.5 kN -16.2 kN	
cycle nr.	1000	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		-
16.7		41.9
33.3		35.7
50		35.7
66.7		35.2
83.3		34.7
100		35
83.3		32.8
66.7		31.3
50		29.3
33.3		25.6
16.7		15.2
0		-
minimum load		-
0		-

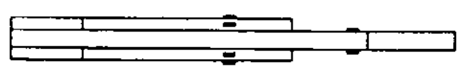


TABLE 5-16
Values of load transfer and secondary
bending ratio - The Netherlands

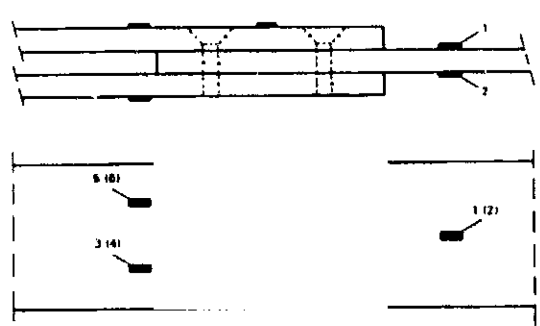
Specimen type Specimen number Max. load (MPa) Min. load (MPa)	1½ DOGBONE DOUBLE SHEAR 4B11 FRFS-B 250 MPa, 60.5 kN -16.2 kN	
cycle nr.	1000	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		-
16.7		47.5
33.3		47.3
50		45.9
66.7		43.6
83.3		42.0
100		40.3
83.3		40.3
66.7		39.8
50		40.4
33.3		41.2
16.7		42.2
0		-
minimum load		48.1
0		-

FIGURE SEE TABLE 5-15

TABLE 5-17
Values of load transfer and secondary bending ratio - USA

Specimen type	DOUBLE SHEAR EQUIVALENT
Specimen number	01-1
Max. load (MPa)	196.85
Min. load (MPa)	0
Test run, cycle nr.	1

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred $1 - \left[\frac{7+8}{3+5}\right] \times 100\ \%$	strain at gauge nr. 3	5	7	8
0		-	-	-	-	-
16.7		1-77 = 23	191	192	146	148
33.3		1-67 = 33	405	404	267	279
50		1-59 = 41	628	628	365	381
66.7		1-55 = 45	853	855	468	471
83.3		1-52 = 48	1077	1083	564	562
100		1-50 = 50	1302	1312	648	652
83.3		1-51 = 49	1070	1085	550	552
66.7		1-53 = 47	853	860	457	453
50		1-57 = 43	630	632	357	363
33.3		1-62 = 38	407	408	248	255
16.7		1-68 = 32	196	196	133	132
0		-	-	-	-	-
minimum load		-see note-				
0		-				



NOTE:
STRAIN GAUGE INSTRUMENTATION NOT ACCORDING TO FRFS PROCEDURES

USA

Fig. 5-1 Secondary bending and load transfer of reverse double dogbone specimen - France

Fig. 5-2a Secondary bending and load transfer of type C lap joint - France

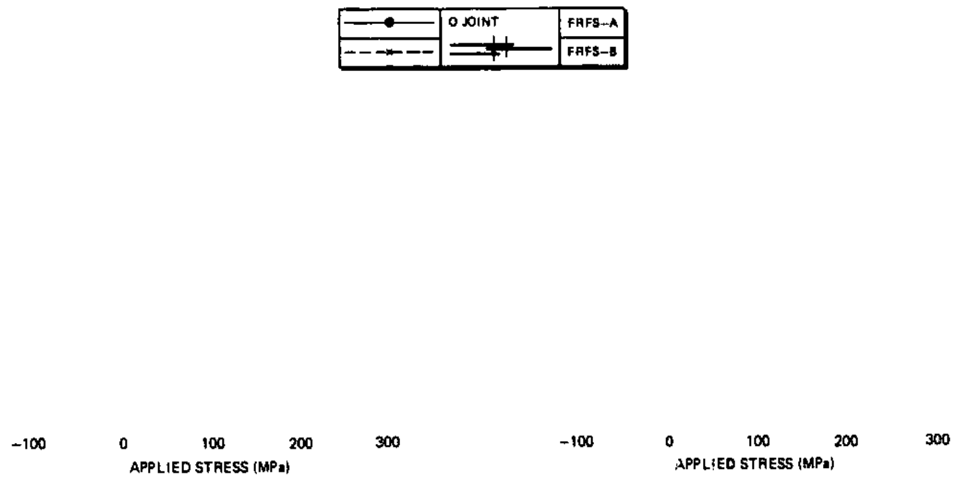


Fig. 5-2b Secondary bending and load transfer of the Q joint - UK

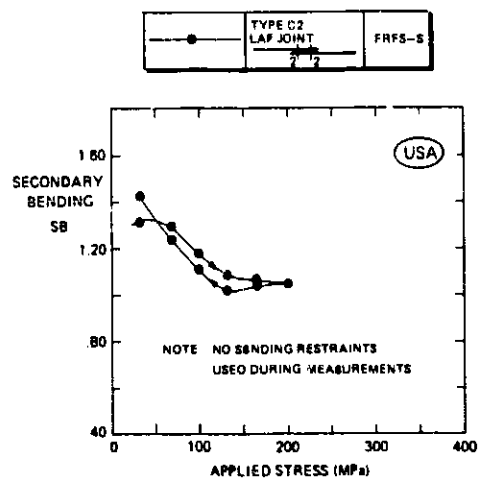


Fig. 5-2c Secondary bending of the type C2 lap joint - USA

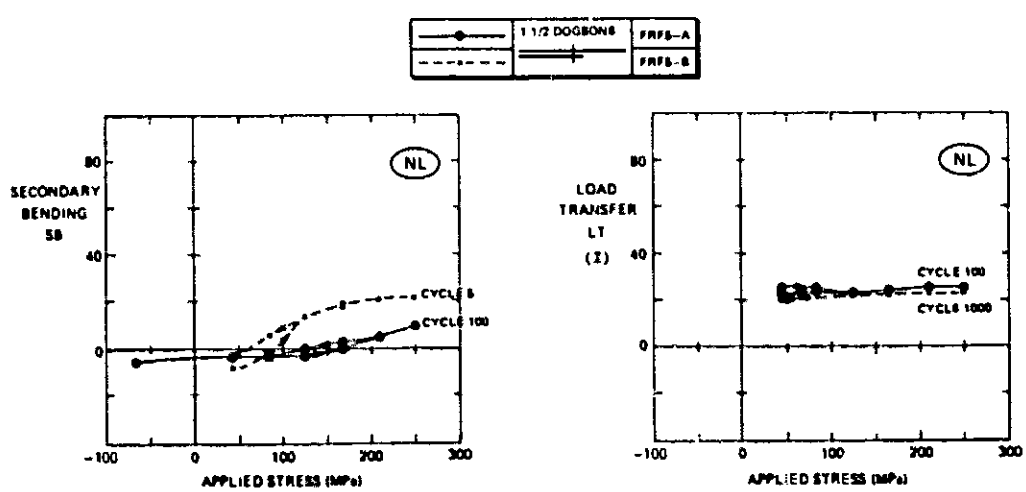
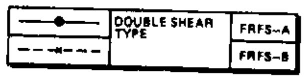


Fig. 5-2d Secondary bending and load transfer of 1½ dogbone joint - the Netherlands



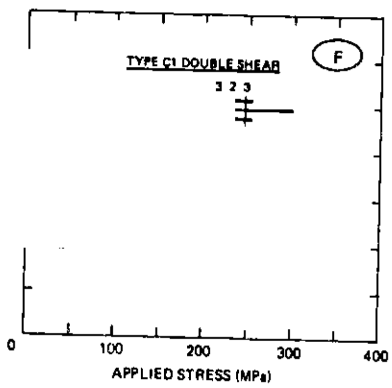


Fig. 5-3a Load transfer of type C1 double shear joint - France

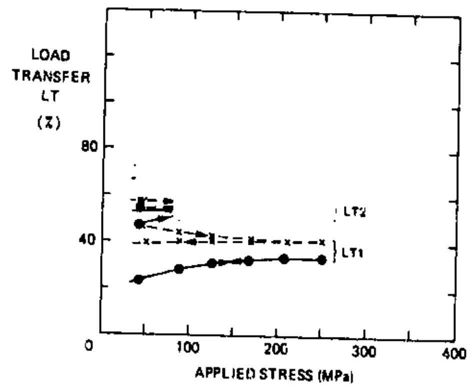


Fig. 5-3b Load transfer of type D double shear joint - France

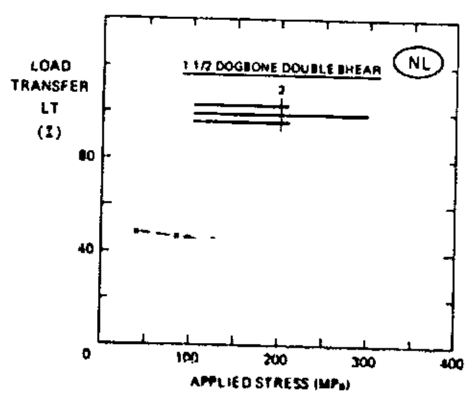


Fig. 5-3c Load transfer of 1½ dogbone double shear joint - the Netherlands

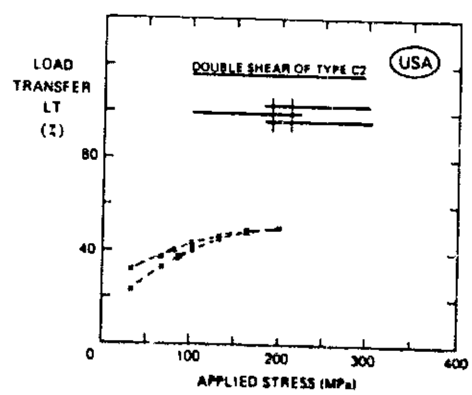


Fig. 5-3d Load transfer of type C2 double shear joint - USA

ANNEX 6

TABULAR PRESENTATION OF THE FATIGUE LIFE DATA

The complete set of fatigue life data for the FRFS programme is given in table 6-1 to 6-21; the framed numbers are the log mean life figures.

TABLE 6-1
Open hole specimen results - Sweden

OPEN HOLE SPECIMEN		SWEDEN		
MATERIAL	HOLE	LOAD LEVEL (MPa), Flights to failure and log mean		
		FALSTAFF		
		150	180	234
2024-T3 t = 5 mm	∅ 6 REAM	83281 92355 25000 251000 124539		6372 5631 6631 619[illegible]
7010-T73651 t = 120 mm 1)	∅ 6 REAM	92150 78845 134558 99249	11452	5359 3572 5172 4626

1) Speciman width in the short transverse direction; specimen thickness = 5 mm

TABLE 6-2
No load transfer joints - France

NO LOAD TRANSFER JOINTS					FRANCE						
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$						
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT (μm)	FALSTAFF						
					200	223	260	290	300	351.6	392.5
2024-T351	ANODIZE PRIMER SEALANT				82973 78139 30960 $\boxed{58550}$		24925 29150 27173 $\boxed{27000}$		2052 2000 $\boxed{2016}$	173 173 81 $\boxed{134}$	
2214-T651	FAST. DRY INST.				60032 >133840 69632 $\boxed{82400}$		23232 24173 24081 $\boxed{23800}$			8225 7373 7373 $\boxed{7650}$	
7475-T7361		BROACH	LOCKBOLT	INTERFER- ENCE 16-32	43344 35160 68234 $\boxed{47000}$		13432 14726 12760 $\boxed{13600}$			373 432 573 $\boxed{452}$	
7050-T7651					81560 >168287 81755 $\boxed{103900}$					10173 8930 8426 $\boxed{9150}$	
2024-T351	BARE					61684 83428 66832 $\boxed{70060}$		3831 6232 4973 3232 $\boxed{4430}$			25 12 $\boxed{17}$

log
mean
life

TABLE 6-3
No load transfer joints - Sweden

NO LOAD TRANSFER JOINTS					SWEDEN	
MATERIAL		FASTENER SYSTEM			FALSTAFF (MPa)	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	200 MPa	280 MPa
2024-T3	EPOXY PRIMER SEALANT	REAM	HLM-11-06-11 Ø 5.990	INT. AVE.-7	>120000 75851 112572	3772 7031 8572
7010- T73651 1)	PR1431G			INT.-28 TO CLEAR +10	44972 27929 74170	7031 5572 10172

1) Specimen width in the short transverse direction.
t = 120 mm - t = 5 mm

TABLE 6-4
No load transfer joints - France

LOW LOAD TRANSFER JOINTS					FRANCE							
REVERSE DOUBLE DOGBONE												
MATERIAL	FASTENER SYSTEM				LOAD LEVEL (MPa) FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$							
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT (µm)	FALSTAFF			MINI-TWIST III			CAL. & = 0.1	
					200	260	351.6	96	109	130	180	225
2024-T351	ANODIZING PRIMER SEALANT	BROACH	LOCKBOLT	INTERFERENCE 16-32	> 108716 > 120478 > $\boxed{114450}$	17232 17225 11913 $\boxed{15260}$	232 373 432 $\boxed{335}$	log mean life				
7050-T7451					85432 > 110000 71130 $\boxed{94960}$	26150 23518 20905 $\boxed{23560}$	6425 6422 1432 6312 $\boxed{6630}$					
2024-T351	ALODINE PRIMER SEALANT	REAM	HI-LOK	INTERFERENCE 80				86311 319538 253656 159006 $\boxed{198450}$	66190 108412 18324 $\boxed{51189}$	9318 9119 $\boxed{9241}$	296860 246650 271920 $\boxed{202385}$	155360 159580 $\boxed{157456}$
7075-T7351								41160 51550 241653 81656 $\boxed{85560}$	18836 54106 83841 74365 31665 $\boxed{50046}$	31665 18836 $\boxed{24430}$	227730 122130 170510 $\boxed{168000}$	68480 49820 $\boxed{58230}$
7050-T7651								113578 101377 98856 $\boxed{104350}$	38836 89318 10190 $\boxed{34500}$	44613 38196 $\boxed{41200}$	184360 137670 139120 $\boxed{159500}$	85640 38230 $\boxed{60940}$

TABLE 6-5
Low load transfer joints - Germany

LOW LOAD TRANSFER JOINTS					FED. REP. GERMANY							
REVERSE DOUBLE DOGBONE												
MATERIAL		FASTENER SYSTEM			FALSTAFF		FALSTAFF		FALSTAFF		FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	LOAD LEVEL (MPa)	FLIGHTS TO FAILURE	LOAD LEVEL	FLIGHTS TO FAILURE	LOAD LEVEL	FLIGHTS TO FAILURE	LOAD LEVEL	FLIGHTS TO FAILURE
2024-T3	ANODIZING PRIMER SEALANT	REAM	HI-LOK	INTERFERENCE 17	170 190 210 230	83031 58431 27400 13172	230 243 245 255	19772 15872 10759 12359	263 275 285 295	11011 5372 3172 2172	295 305 315	2172 1372 1031
		NO DRILL		INTERFERENCE 36	190 200 210 220	57400 38126 35772 20372	225 230 245 250	33024 26729 22372 21972	255 265 275 285	12871 8831 11172 1759	295 305 315	1431 1372 1372
7050-T76		REAM		INTERFERENCE 22	210 230	61372 16372	255 275	11372 12000	285 295	8145 7731		
		NO DRILL		INTERFERENCE 40	253 295	10972 16259	265 293	12541 11172	340 340	7611 6159		
		REAM		CLEARANCE 18	230 255	30624 18539	275 285	8267 1779	293 305	7772 5431		
		REAM	[illegible]	INTERFERENCE 11	170 180 190 200	37031 32172 26776 20577	210 230 235 275	14572 10772 9177 6979	305 315 340 350	7625 6024 4972 2031	380 380 420	2172 1729 631
		DRILL		INTERFERENCE 31	180 200 210 220	31159 20772 34372 21531	225 230 243 255	22231 16729 14631 14833	265 285 315 340	11129 12011 7221 4031	330 380 380 420	4372 3372 3372 559
		DRILL	[illegible]	INTERFERENCE 42	197 200 210	17031 38011 22520	230 233 235	35031 16772 13773	293 315 340	10631 10321 7925	380 400 420	5172 4831 872
	PRIMER SEALANT	TAPERLOK REAMED	TAPERLOK	INTERFERENCE 33	215 225 230	56172 34377 29977	276 290 310	23572 14726 16700	330 340 360	8031 9172 7851	399 405 415	4372 2972 4372

TABLE 6-6
Low load transfer joints - Italy

LOW LOAD TRANSFER JOINTS					ITALY	
REVERSE DOUBLE DOGBONE						
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
					FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	280	351.6
2024-T3	ANODIZING PRIMER SEALANT	REAM	HI-LOK Ti CSK Ø 5	INTERFERENCE 13-43	29125 31373 26232 34929 23628 28791	log mean life
			HI-LOK Ti CSK Ø 6 TYPE LN29797		22061 17032 19820 20032 16632 19008	773 832 832 632 768 764
			HI-LOK TENSION Ti CSK Ø 6		10026 18232 12625 13080 27276 15245	773 373 432 373 373 444
			HI-LOK Ti PROT- RUDING Ø 6		19302 21437 18424 22432 25360 21253	
			HI-LOK Ti CSK Ø 8	INTERFERENCE 14-51	26673 21432 25773 13232 20573 20924	
		COLD WORK REAM	BOLT Ti CSK Ø 6	CLEARANCE 10-40	3929 4142 3574 3726 3837	232 432 373 373 432 360
		REAM	HI-LOK Ti CSK Ø 6 TYPE MSTM11	INTERFERENCE 13-43	27203 16425 16867 14715 17863 18180	
		COLD WORK REAM	BOLT Ti CSK Ø 6		39308 30013 28491 34832 41872 35395	832 632 626 632 632 666

TABLE 6-7
Low load transfer joints - The Netherlands

LOW LOAD TRANSFER JOINTS					THE NETHERLANDS				
REVERSE DOUBLE DOGBONE									
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN				
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	FALSTAFF		MINITWIST III		
					280	351.6	70	85	100
7050-T76	PRIMER SEALANT FAST. WET INST. WITH SEALANT	DM DRILL	HI-LOK PROTRUDING	CLEARANCE 25- INT. 76	14111 23772 24560 20440	8325 9159 8732	log mean life	66323 > 148000 > 175000 261655 > 145604	32106 48412 77378 > 98632 > 58687
		STANDARD DRILL		CLEARANCE 63-255	6372 7124 8929 7401	2129 2231 2179		22790 26681 26858 25369	25656 16095 17378 19268
2024-T3	ANO-DIZING PRIMER SEALANT FAST.WET INSTAL. WITH SEALANT	DM DRILL	HI-LOK CSK	INTERFER-ENCE 20-40			253646 359896 > 400000 331758	120501 124708 147856 130194	56106 75260 54981

TABLE 6-8
Low load transfer joints - United Kingdom

LOW LOAD TRANSFER JOINTS					UNITED KINGDOM	
REVERSE DOUBLE DOGBONE UK-DESIGN						
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	FALSTAFF	
					164 (= 280 NET)	206 (= 350 NET)
7050-T7651	ALOCHROMED PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 13-61	25231 12372 21359 19292 log mean life $\boxed{18938}$	6631 5711 4929 $\boxed{5715}$
		TAPER REAM	TAPERLOK	INT. 46-106	54231 37772 50631 24831 27863 $\boxed{37254}$	22972 30796 14224 27172 26811 $\boxed{23606}$
		REAM	HI-TIGUE	INT. 76-127	55351 54772 53172 42172 74772 $\boxed{55109}$	17080 17729 22959 21572 23372 $\boxed{20368}$
		REAM	HUCKCRIMP	CLEARANCE 13-48	12929 10724 13172 11011 18959 $\boxed{13069}$	5280 5698 6128 5024 5024 $\boxed{5414}$
		DRILL HUCK MANDRELL COLD WORK	HUCK EXL	INT. 38-144	27531 80280 120272 39759 36431 $\boxed{52132}$	14224 20631 26490 39111 24205 $\boxed{23625}$
		SPLIT SLEEVE COLD WORK REAM	HI-LOK	TRANSITION: 13 CLEAR. TO 39 INT.	72372 82172 40529 43372 60572 $\boxed{57585}$	14725 20711 18031 23359 16559 $\boxed{18431}$
		ACRES SLEEVE COLD WORK	HI-LOK	TRANSITION: 13 CLEAR. TO 13 INT.	54625 34372 60511 38231 44231 $\boxed{45364}$	19372 17031 21231 22989 19972 $\boxed{20020}$
	REVERSE DOUBLE DOGBONE AGARD DESIGN					
		REAM	HI-LOK	CLEARANCE 13-61	26337 19972 21724 24129 23172 $\boxed{22966}$	6221 7031 6011 4480 4729 $\boxed{5613}$
		SPLIT SLEEVE COLD WORK REAM	HI-LOK	TRANSITION: 13 CLEAR. TO 39 INT.	136464 173572 50759 178745 240231 $\boxed{138859}$	19172 33880 32031 22329 39824 $\boxed{28408}$

TABLE 6-9
Low load transfer joints - USA

LOW LOAD TRANSFER JOINTS				USA
REVERSE DOUBLE DOGBONE				
MATERIAL		HOLE QUALITY	FASTENER	LOAD LEVEL (MPa), FLIGHTS TO FAILURE
ALLOY	FAYING SURFACE			FALSTAFF 261.9
2024-T3 CLAD t = 3.2		STANDARD DRILL, DEBURR	RIVET 2024 HAND BUCKED (ICE BOX)	4372 5772 2572 $\boxed{4019}$ log mean life
			RIVET 2024 MACHINE SQUEEZED (ICE BOX)	1372 3572 $\boxed{2214}$
			RIVET 7050 HAND BUCKED	2024 3480 $\boxed{2654}$
			RIVET 7050 MACHINE SQUEEZED	2231 2430 $\boxed{2328}$

TABLE 6-10
Type D double shear joint - France

DOUBLE SHEAR JOINTS					FRANCE					
TYPE D JOINT										
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$					
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	FALSTAFF			CAL R=.1	MINI-TWIST	
					200	250	300	180	109	130
2024-T351	ALODINE PRIMER	REAM	HI-LOK	INTERFERENCE 80	>139726 233130 >174000 >272195 >$\boxed{198187}$ log mean life	64797 73973 40573 $\boxed{57940}$	13373 23760 39173 $\boxed{23200}$	126750 285020 187560 265210 $\boxed{205891}$	117653 98856 73656 87513 $\boxed{93000}$	25656 9656 21656 18856 $\boxed{17850}$
7075-T7351	ALODINE PRIMER	REAM	HI-LOK		138373 94832 $\boxed{114550}$	79740 47295 59573 $\boxed{43760}$	41226 30422 21632 $\boxed{30050}$	184070 225630 395080 185550 189710 $\boxed{225000}$	136412 98786 65099 108095 $\boxed{98700}$	50682 41656 45656 62682 $\boxed{49600}$
7050-T7651	EPOXY PAINT	BROACH FRFS-A'		CLEARANCE 10-30	9179 9373 10973 $\boxed{9810}$	3730 4912 3373 $\boxed{3954}$				
		COLD WORK BROACH FRFS-B'		INTERFERENCE 15-35	69760 85032 50025 $\boxed{58725}$	16632 15773 28730 24432 $\boxed{20717}$				
	ALODINE PRIMER	REAM	HI-LOK	INTERFERENCE 80		45973 18832 51573 $\boxed{35500}$			87391 134936 52965 88412 $\boxed{86200}$	
					144773 113373 $\boxed{128116}$	55032 36797 50973 $\boxed{46900}$	27225 40832 20632 $\boxed{26400}$	195400 139340 120720 161410 163510 $\boxed{154000}$	82682 66857 83841 71671 $\boxed{75900}$	24501 41851 25556 33099 $\boxed{30550}$

TABLE 6-11
Medium load transfer double shear joint - The Netherlands

DOUBLE SHEAR JOINTS TYPE M1 & M2-MEDIUM LOAD TRANSFER					THE NETHERLANDS				
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$				
					MINI-TWIST			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	70	85	100	200	250
2024-T3	ANODIZE PRIMER SEALANT	DOUBLE MARGIN DRILL	HI-LOK	INTERFERENCE 20-40	log mean life	99898 183526 >315666 $\boxed{>179540}$	> 57120 > 87716 112446 > $\boxed{82592}$		
		REAM		INTERFERENCE 80-100	>400000 > $\boxed{400000}$	164412 >250320 >259395 $\boxed{>220190}$	> 57377 78073 > $\boxed{66929}$		
7050-T76	PRIMER SEALANT	REAM FRFS-A	HI-LOK TEST SERIES NOT COMPLETED	CLEARANCE 10-30				34432 .... $\boxed{.....}$	11832 .... $\boxed{.....}$
		COLD WORK FRFS-B		INTERFERENCE 15-35				>16773 .... $\boxed{.....}$	>16044 .... $\boxed{.....}$

TABLE 6-12
High load transfer double shear joint - The Netherlands

DOUBLE SHEAR JOINTS TYPE H1 HIGH LOAD TRANSFER					THE NETHERLANDS				
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$				
					MINI-TWIST III			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	70	85	100	200	250
2024-T3	ANODIZE PRIMER SEALANT	DOUBLE MARGIN DRILL	HI-LOK	INTERFERENCE 20-40 log mean life	307691 $\boxed{307691}$	56921 98496 121656 $\boxed{88025}$	12412 24411 $\boxed{17407}$		
		REAM		INTERFERENCE 80-100	156684 157655 $\boxed{157169}$	50991 61031 $\boxed{55786}$	31691 $\boxed{31691}$		
		COLD WORK REAM		CLEARANCE 0-25	>400000 $\boxed{>400000}$	93197 106856 121578 $\boxed{106582}$	13653 48413 $\boxed{25709}$		
7050-T76	PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 10-30				14432 15468 .... $\boxed{.....}$	4041 5848 9573 5329 $\boxed{5892}$
		COLD WORK REAM		INTERFERENCE 15-35				>18636 >34529 .... $\boxed{.....}$	8432 9625 13832 >14200 > $\boxed{11236}$

TABLE 6-13
High load transfer double shear joint - United Kingdom

DOUBLE SHEAR JOINTS					UNITED KINGDOM	
TYPE H2 - HIGH LOAD TRANSFER					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	191 280 NET	256 375 NET
7010-T7651	ALOCROME PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 13-61	37898 23172 30839 34929 14821 log $\boxed{26875}$ mean life	7572 4031 3559 3431 2959 $\boxed{4060}$
		TAPER REAM	TAPERLOK	INTERFERENCE 46-106	172929 91211 191085 134759 $\boxed{141963}$	21421 42929 29206 47772 $\boxed{33655}$
		REAM	HI-TIGUE	INTERFERENCE 76-127	66624 32796 52172 123227 41024 $\boxed{56510}$	34224 27749 27031 12972 20924 $\boxed{23368}$
		REAM	HUCKCRIMP	CLEARANCE 13-48	50911 14825 45274 143431 114529 $\boxed{56214}$	18943 14329 17031 20572 19524 $\boxed{17937}$
		DRILL HUCK MANDEL COLD WORK	HUCK EXL.	INTERFERENCE 38-144	211711 155031 155172 96996 146572 $\boxed{148580}$	87511 58880 55172 59929 52972 $\boxed{61814}$
		SPLIT SLEEVE COLD WORK REAM	HI-LOK	TRANSITION: 13 CLEAR. TO 39 INT.	51172 76759 > 224420 166196 93021 $\boxed{106386}$	31759 34525 27772 27359 $\boxed{30212}$
		ACRES SLEEVE COLD WORK	HI-LOK	TRANSITION 13 CLEAR. TO 13 INT.	124759 41929 45637 $\boxed{62034}$	13624 9031 16972 12329 30621 $\boxed{15113}$

TABLE 6-14
Type C lap joint - France

SINGLE SHEAR JOINTS					FRANCE		
	TYPE C LAP JOINT 323						
MATERIAL	FASTENER SYSTEM				LOAD LEVEL, FLIGHTS TO FAILURE AND LOG MEAN		
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	FALSTaFF		
					112.5	150	200
2024-T3	ANODIZING PRIMER SEALANT	BROACH	LOCKBOLT	INTERFERENCE 16-22	53634 63426 71596 log mean life 62450	10606 15432 14832 13440	1431 1432 1130 1320
2214-T651					41825 64944 56522 53550	16232 19822 20973 18900	3432 2925 4832 3650
7475-T7351					36206 26712 41625 34270	8330 12330 13185 11060	1681 1573 1112 1430
7050-T765	EPOXY PAINT	REAM FRFS-A	HI-LOK			9032 9632 8960 12144 9860	2981 3973 2573 2832 3050
		COLD WORK REAM FRFS-B				8832 13730 12173 7944 10410	3373 4973 3373 3840

TABLE 6-15
Q-type joint - United Kingdom

SINGLE SHEAR JOINTS					UNITED KINGDOM	
Q-JOINT					LOAD LEVEL (MPa), FLIGHTS TO FAILURE LOG MEAN	
MATERIAL		FASTENER SYSTEM				
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	FALSTAFF	
					191 280 NET	263 350 NET
7050-T76	PRIMER SEALANT	REAM FRFS-A	HI-LOK	CLEARANCE 10-30	12128 14431 12160 13831 log 14031 mean life 13280	3925 2929 3444 4336 3639
		COLD WORK REAM FRFS-B		INTERFERENCE 15-35	9631 12424 12329 16224 17631 13337	3801 3172 3624 5323 3905

TABLE 6-16
1½ Dogbone joint - USA

SINGLE SHEAR JOINTS					USA
1½ DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN
MATERIAL		FASTENER SYSTEM			
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	FALSTAFF
					238
7075-T76 BARE t=3.2	ANODIZE PRIMER TOPCOAT[1)] 1) not on faying surface	REAM	HI-LOK	SLIGHT PRESS	16772 22572 25529 19972 log mean life 20961
		REAM	SLEEVBOLT	INTERFERENCE 64	23231 28729 16117 22073

TABLE 6-17
Type C2 lap joint - USA

SINGLE SHEAR JOINT / TYPE C2 LAP JOINT					USA		
MATERIAL		FASTENER SYSTEM			LOAD LEVEL, FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$	LOAD LEVEL, FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$	
					FALSTAFF	FALSTAFF	
ALLOY	THICK-NESS (inch)	FAYING SURFACE	HOLE QUALITY	FASTENER	200	150	200
2024-T3 CLAD	.63		STANDARD DRILL DEBURR	RIVET 2024-T3 (DD)-Ø3/16- SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD			
				RIVET 7050-T73 (E)-Ø3/16- SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD	4880 5831 11159 $\boxed{6822}$		
	.090			RIVET 2024-T3 (DD)-Ø1/4- SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD	2775 5031 2359 $\boxed{3205}$		
				RIVET 7050-T73 (E)-Ø1/4- SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD	4824 4031 $\boxed{4410}$		
	.100			RIVET 2024-T3 (DD)-Ø3/16- SQUEEZE-MS20426 COUNTERSUNK HEAD	1772 2031 999 1372 $\boxed{1490}$		
				RIVET 7050-T73 (E)-Ø3/16- SQUEEZE-MS20426 COUNTERSUNK HEAD	1172 1221 2129 1080 $\boxed{1347}$		
	.160			RIVET 2024-T3 (DD)-Ø1/4- SQUEEZE-MS20426 COUNTERSUNK HEAD	4811 4396 4743 log 3711 mean $\boxed{4392}$ life		
				RIVET 7050-T73 (E)-Ø1/4- SQUEEZE-MS20426 COUNTERSUNK HEAD	10830 14000 7996 10329 $\boxed{10578}$		
				RIVET 2024-T3 (DD)-Ø1/4- SQUEEZE-BRFR8DD9 BRILES FLUSH HEAD	3372 1631 4221 2124 $\boxed{2650}$		
				RIVET 7050-T73 (E)-Ø1/4- SQUEEZE-BRFR8E9 BRILES FLUSH HEAD	6311 1) 8580 1) 9326 1) 15000 2) $\boxed{9303}$		
7050-T76	5	PRIMER SEALANT	REAM FRFS-A	HI-LOK CLEARANCE		26059 14812 22201 34925 33832 $\boxed{25464}$	15370 13463 18000 5960 5626 $\boxed{10455}$
			COLD WORK REAM FRFS-B	INTERFERENCE		53432 21773 41300 18642 56118 $\boxed{34430}$	12639 19281 9173 8425 $\boxed{11715}$

1) BRFR System "A" fastener
2) BRFR System "R" fastener

TABLE 6-18
1½ Dogbone joint - The Netherlands

SINGLE SHEAR JOINTS					THE NETHERLANDS	
1½ DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	200	250
7050-T76	PRIMER SEALANT	REAM FRFS-A	HI-LOK	CLEARANCE 10-30	18411 60372 56972 63831 log mean life $\boxed{44839}$	9559 15419 23373 22231 $\boxed{16635}$
		COLD WORK REAM FRFS-B		INTERFERENCE 15-35	29572 40431 58231 35759 $\boxed{39722}$	13524 14231 17962 19172 $\boxed{16045}$

TABLE 6-19
Single shear X joint - Sweden

SINGLE SHEAR X JOINT				SWEDEN	
MATERIAL	FASTENER SYSTEM			FALSTAFF	
ALLOY	HOLE QUALITY	FASTENER	FIT	150 MPa	200 MPa
2024-T3	REAM	HLM-11-06-05	INT. AV.-7: -28 → +10	112081	10211 18359 8711 $\boxed{11776}$
7050-T76	REAM FRFS-A*	HL-19-8-7	CLEAR. 29: +22 → +47	13860 16972 13180 log mean life $\boxed{14582}$	5329 5590 6280 $\boxed{5721}$
7050-T76	COLD WORK REAM FRFS-B*	HL-19-8-7	CLEAR +9: +2 → +26	42772 30224	10929 11972 11372 $\boxed{11416}$

NOTE: FRFS-A*: falling + 10 µm outside the specification of FRFS-A
FRFS-B*: ~10 µm clearance instead of 25 µm interference

TABLE 6-20
Type C1 double shear joint - France

DOUBLE SHEAR EQUIVALENT JOINT					FRANCE		
323 TYPE C1					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$		
MATERIAL		FASTENER SYSTEM			FALSTAFF		
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT	150	200	250
7050-T7651	EPOXY PAINT FASTENERS WET INSTALLED	FRFS-A	HI-LOK	CLEARANCE 10-30	106490 log mean life $\boxed{106490}$	38373 23912 22637 21797 $\boxed{25940}$	8825 9173 10973 $\boxed{9613}$
		FRFS-B		INTERFERENCE 15-35		86360 79573 89832 41899 46432 $\boxed{65450}$	28628 29160 27530 $\boxed{28430}$

TABLE 6-21
1½ Double shear joint - The Netherlands

DOUBLE SHEAR JOINTS					THE NETHERLANDS	
1½ DOUBLE SHEAR DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND $\boxed{\text{LOG MEAN}}$	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	200	250
7050-T76	PRIMER SEALANT FASTENER WET INSTALLED	REAM FRFS-A	HI-LOK	CLEARANCE 10-30	28329 49772 28638 32631 log mean life $\boxed{33880}$	14772 16924 12372 18372 $\boxed{15440}$
		COLD WORK REAM FRFS-B		INTERFERENCE 15-35	> 54756 > 99980 121394 $\boxed{87266}$	58172 90831 99211 93572 $\boxed{83688}$

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-R-721	ISBN 92-835-1512-9	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title

FATIGUE RATED FASTENER SYSTEMS

7. Presented at

8. Author(s)/Editor(s)	9. Date
edited by H.H.van der Linden	November 1985

10. Author's/Editor's Address	11. Pages
Various	94

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Fasteners
Fatigue (materials)
Fatigue tests
Mechanical engineering

14. Abstract

In recent years the aerospace industry has developed many ways of joining parts together; despite all innovations, however, the most common means of doing this remains the mechanical fastener. The designer needs to know which fastener systems are the most efficient from his point of view; this report is the outcome of a collaborative programme (sponsored by the Structures and Materials Panel of AGARD) which aimed to evaluate some of the available Fatigue-rated Fastener Systems. The programme studied a number of systems; tests covered not only the fasteners themselves but also the preparation of the holes and the quality of fit.

This Report was sponsored by the Structures and Materials Panel of AGARD.

AGARD Report No.721 Advisory Group for Aerospace Research and Development, NATO FATIGUE RATED FASTENER SYSTEMS Edited by H.H.van der Linden Published November 1985 94 pages P.T.O	AGARD-R-721 Fasteners Fatigue (materials) Fatigue tests Mechanical engineering

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AGARD ... h and Advisory Develop FATIGU ... STEMS Edited Publish 94 page In rece ... ed many ways ... ovations, howev ... mains the mecha ... w which fastene ... point of view ... borative progra ... Materials Panel ... ne of the P.T.O	AGARD-R-721 Fasteners Fatigue (materials) Fatigue tests Mechanical engineering